UNIVERSITY OF PUERTO RICO
DEPARTMENT OF MARINE SCIENCES
MAYAGUEZ

FINAL REPORT ON OCEAN THERMAL ENERGY PROJECT

AUGUST 1976

FINAL REPORT

Ocean Thermal Energy Conversion: Resource Assessment and Environmental Impact for Proposed Puerto Rico Site

NSF Grant No. AER 75-00145

August, 1976

by

Donald K. Atwood*, Peter Duncan
Marvel C. Stalcup**, and Michael J. Barcelona

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** Present address, Woods Hole Oceanographic Institution, Woods Hole, Mass., 02543

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ACKNOWLEDGEMENT

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INTRODUCTION

As a combined result of declining fossil fuel reserves and man's increasing technological capability in the oceans, the concept of extracting vast reserves of thermal energy stored in the tropical sea surface by a process called Ocean Thermal Energy Conversion (OTEC) is rapidly approaching a functional reality. As part of a program to exploit this energy reserve the Research Applied to National Needs (RANN) Program of the U.S. National Science Foundation (NSF) has funded a one year study of a specific high potential OTEC site near Puerto Rico. This publication comprises the final report of that study.

The site chosen is near the southeast coast of Puerto Rico just off Point Tuna and close to the town of Yabucoa (See Location Map, Figure 1). It was considered both as a high potential site for an OTEC prototype plant and as a typical "near island" site. The potential of southern coasts of the Greater Antilles for OTEC sites is great and has been discussed in detail elsewhere (Duncan, Atwood, and Stalcup, 1976).

The work reported on consisted of two parts.

Part I - A survey of existing oceanographic and meteorological data at and near the site and for other possible sites near Puerto Rico

Part II - A survey of the specific site to confirm the oceanographic conditions prevalent there.

The first part of the report is derived from a literature survey in which the aim has been to set down the oceanographic and meteorological facts concisely. A complete list of the works consulted is listed in the bibliography, but, references in each section have been kept to a minimum to save the reader a plethora of parenthesis.

Our conclusion is that the specific Yabucoa site is oceanographically excellent for ocean thermal energy conversion and that it is probably typical of several sites along the south coasts of the Greater Antilles.

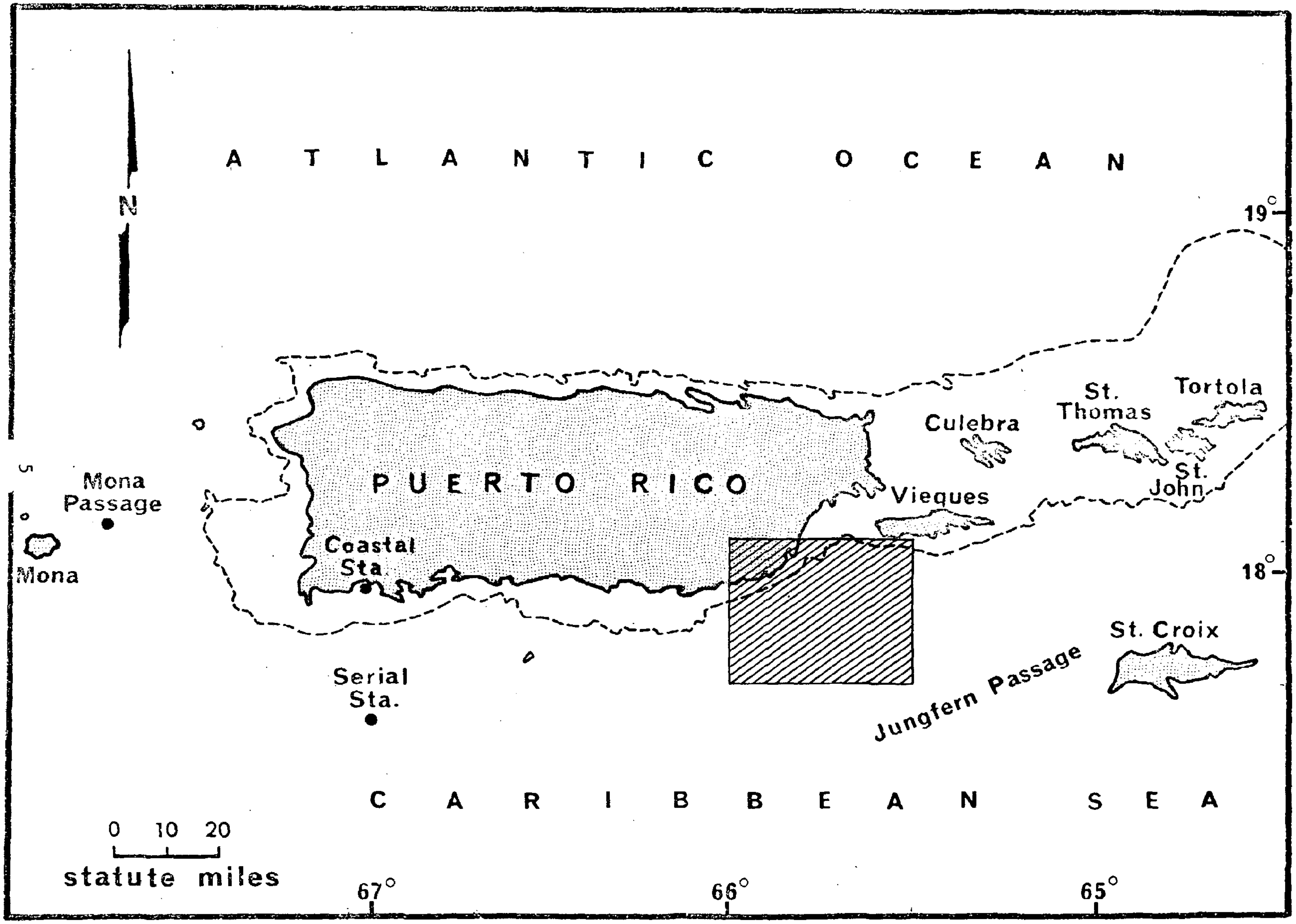


FIG. I LOCATION MAP FOR SURVEY AREA

PART I: SURVEY OF HISTORICAL DATA

I.1 Bathymetry

The site surveyed is located to the south-east of the island of Puerto Rico, on the Caribbean side of the Puerto Rico - Virgin Island shelf (see Figure 2). The narrow continental shelf and steep continental slope at the site ensure that depths in excess of 1000 meters are found within 5 km of the shore, between the island of Puerto Rico and a sill which extends eastwards and separates the Virgin Islands Basin from the Venezuela Basin, in which bottom temperatures are slightly colder than in the Venezuela Basin. Results of more detailed surveys of the site are discussed in Part II of this report (section II.2).

I.2 Bottom Quality

A core taken at 17°46' n, 66°01' W at 1270 meters depth on the island slope of Puerto Rico, some 18 km to the southwest of the site, revealed that the first meter of sediment is a mixture of clay, silt, sand and gravel. In general, the region is one in which the bottom shallower than 200 meters is dominantly gravel and rock, and deeper than this is mud. Data taken from SP189II.

I.3 Seismicity

The following qualitative data is contained in U.S.N.O.O. Pub. No. 700 (V). The entire island of Puerto Rico falls within the seismic area extending from Panama, through the Andes and coastal Venezuela, along the Windward Islands to Cuba. In addition, two submarine faults straddle the island to the north and south. Consequently it falls within a region where earthquakes are reported to be "relatively frequent", with epicenters at depths between 70 and 300 km. Tsunamis have been reported from all Puerto Rican coastal regions facing the Caribbean.

No volcanoes are known in Puerto Rico.

I.4 Climate

The site has a marine tropical climate characterized by a high mean annaul air temperature which varies little with season (80.3° F, ± 3°), and a high mean relative humidity (78%). Figure 3, drawn from data in "Summary of Synoptic Meteorological Observations, Volume 4" (SSMO Vol. 4), illustrates the mean seasonal temperature cycle with an envelope of the observed maxima and minima. Figure 4, from the same source, shows the frequency distribution of relative humidity. SSMO, Vol. 4, is a valuable reference for climatic conditions and should be consulted by those interested in the diurnal variations of wind, cloudiness, fog, relative humidity, etc. Abbreviated tables for oceanic conditions from "Sailing Directions" (H.O. 21) are included here as Figure 5 and Table I.

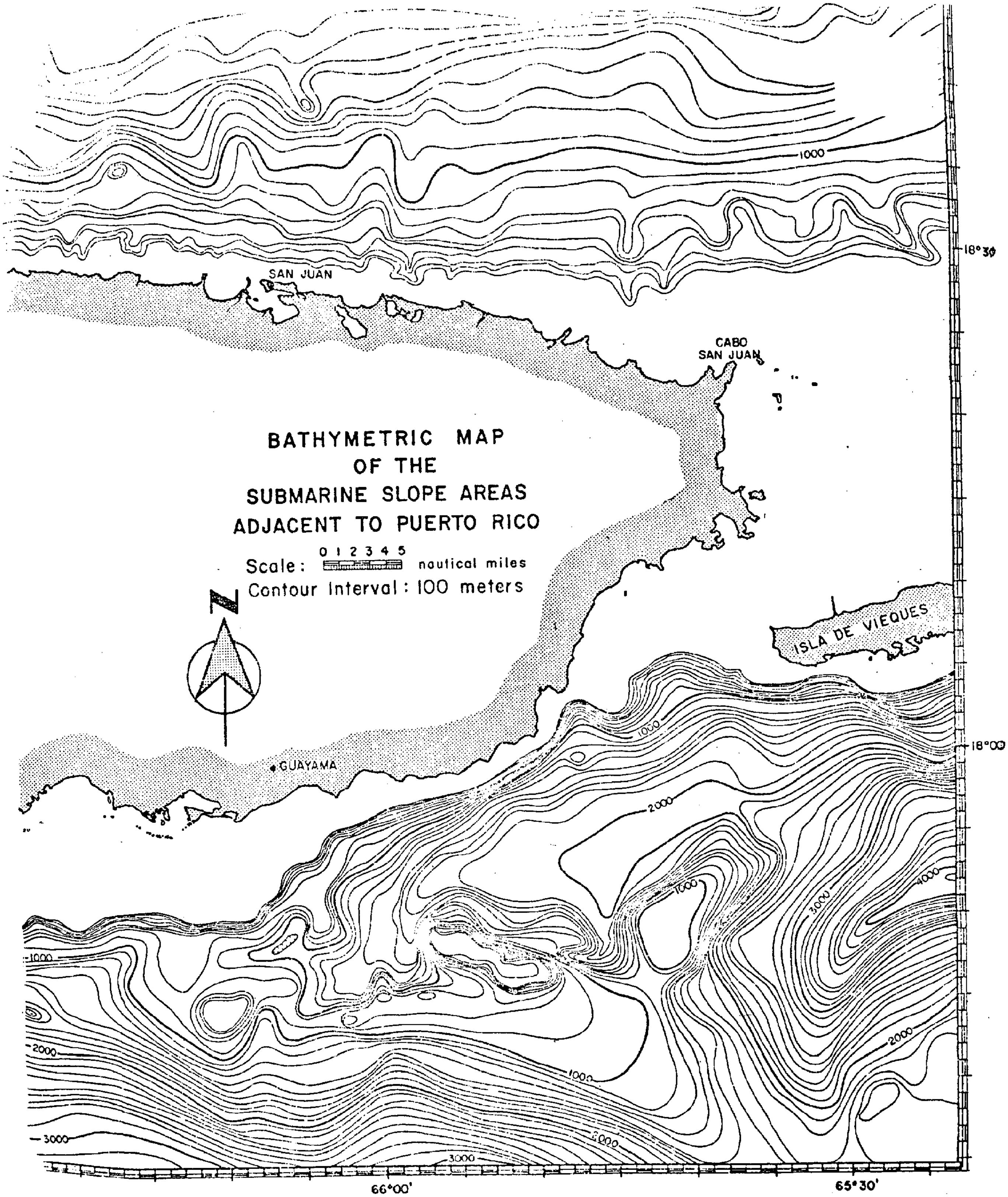
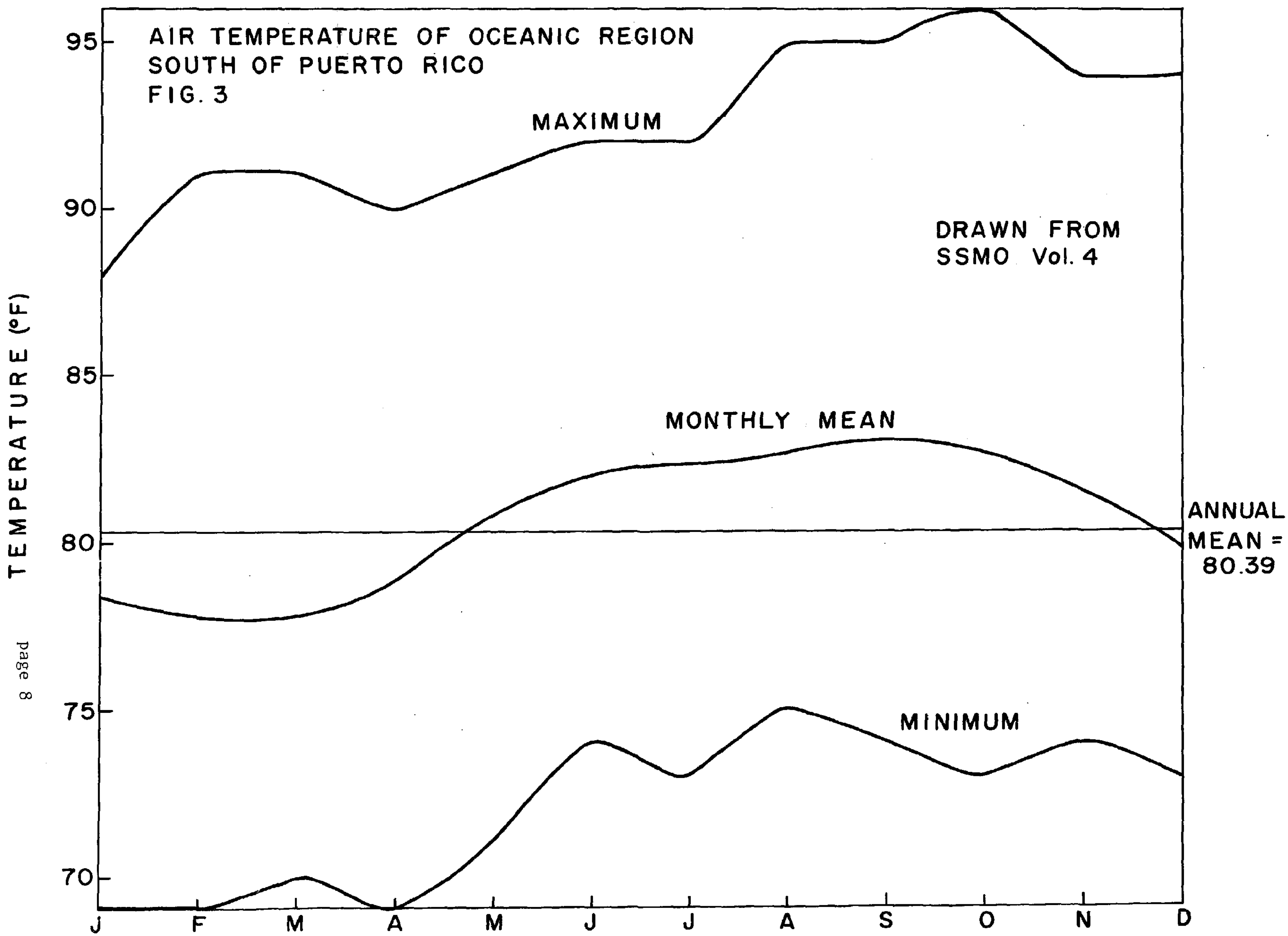


FIG. 2 GENERAL BATHYMETRY MAP


AIR TEMPERATURE OF OCEANIC REGION
SOUTH OF PUERTO RICO
FIG. 3
MAXIMUM
DRAWN FROM
SSMO Vol. 4
MONTHLY MEAN
ANNUAL
MEAN =
80.39
MINIMUM
TEMPERATURE (°F)
95
90
85
80
75
70
J
F
M
A
M
J
J
A
S
O
N
D

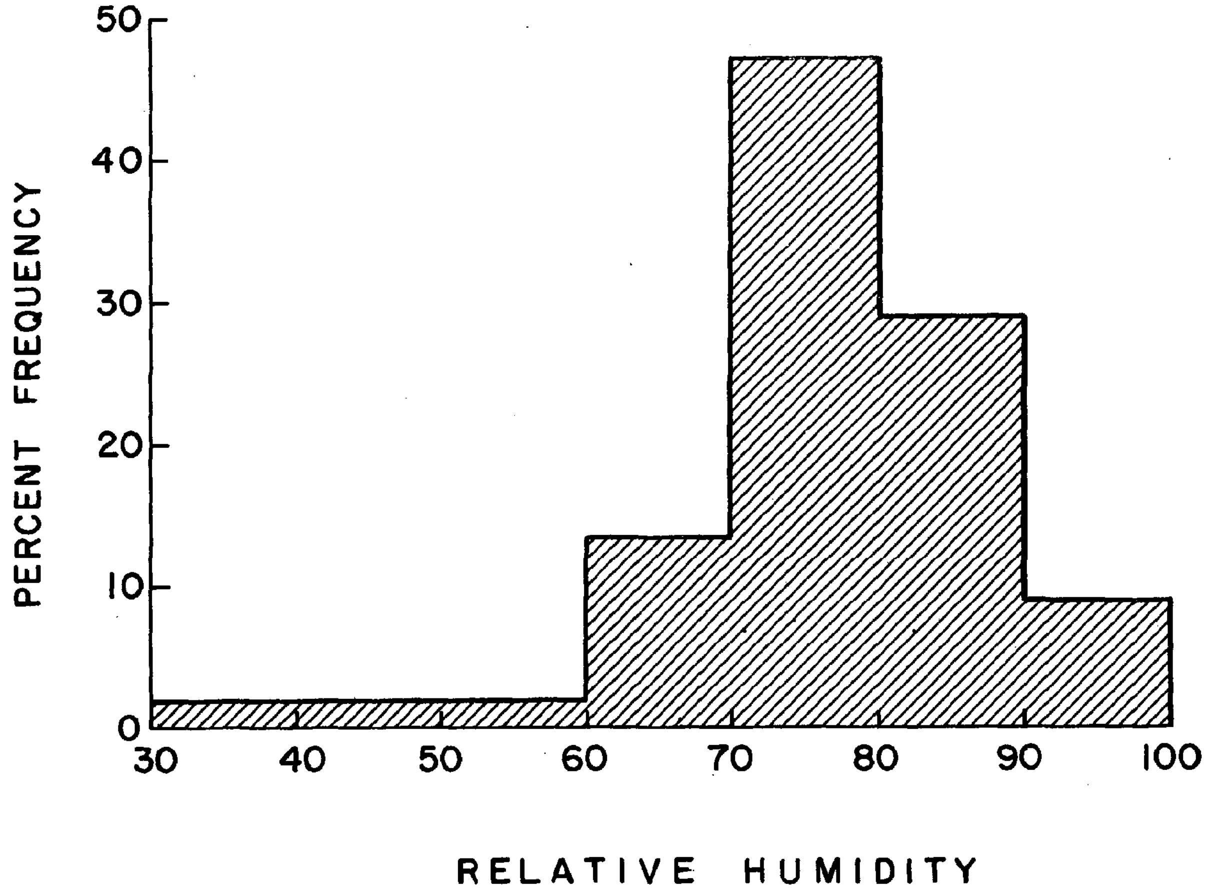


FIG. 4
DISTRIBUTION OF RELATIVE HUMIDITY—OCEANIC REGION SOUTH OF PUERTO RICO.....Dwn. from SSMO, vol. 4

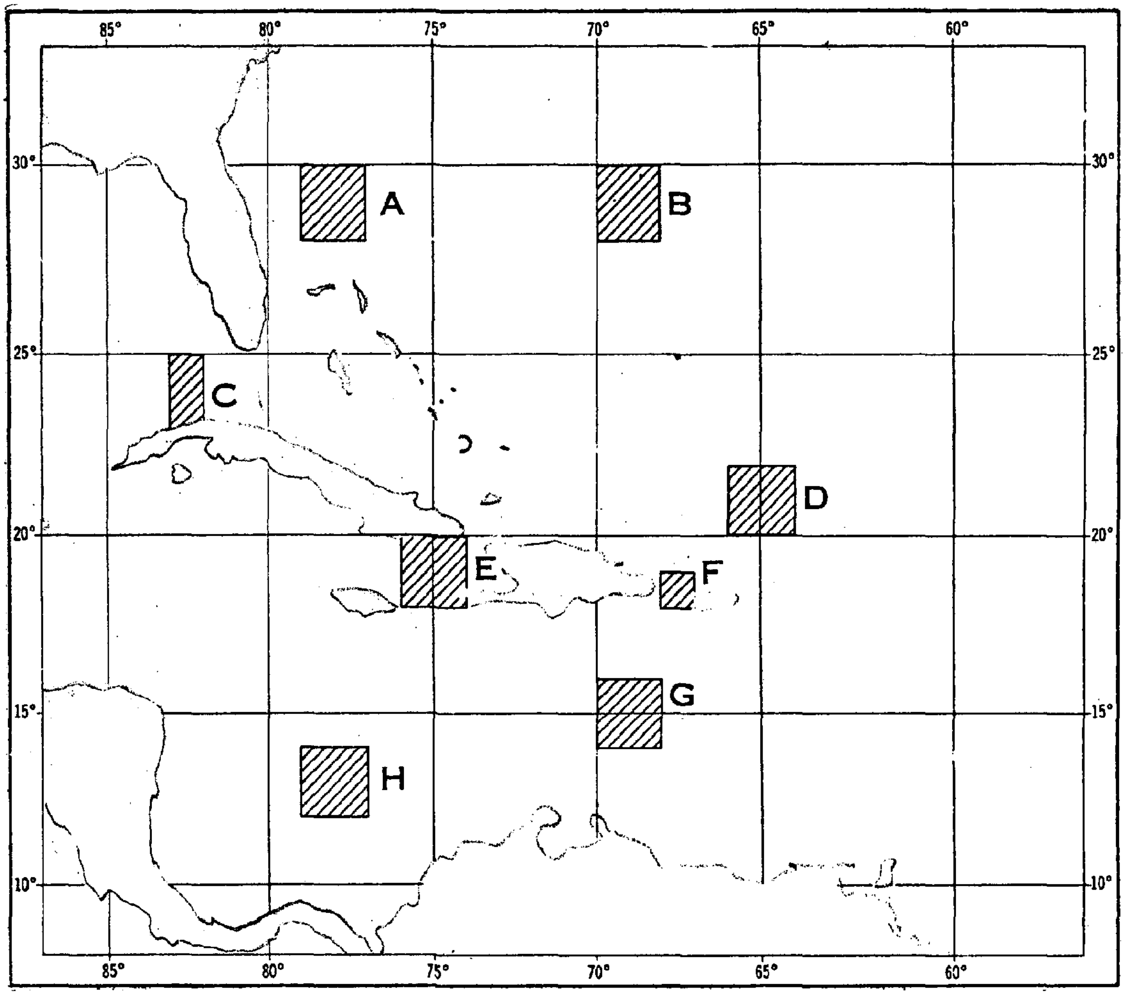


FIG. 5 LOCATION OF OCEAN AREAS F AND G
(From H.O. 21)

UNIT AREA F

Months		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Pressure	¼ of obs. ≦	1017	1017	1016	1016	1016	1016	1017	1016	1016	1016	1016	1016
Sea level pressure	Median	1018	1018	1017	1017	1017	1017	1018	1017	1016	1016	1017	1017
(Millibars)	¼ of obs. ≧	1019	1019	1018	1018	1018	1018	1019	1018	1017	1017	1017	1018
Temperature, air (° F.)	¼ of obs. ≦	76	76	76	77	78	80	80	81	81	80	80	77
	Median	77	77	77	78	80	81	81	82	82	81	81	78
	¼ of obs. ≧	78	78	78	79	82	82	82	83	83	82	82	79
Temperature, mean sea surface (° F.)		78	78	78	79	81	82	82	83	83	83	82	80
Precipitation: Percent of observations with precipitation		3	4	3	4	7	5	3	5	6	7	5	3
Cloudiness: Percent of observations with	≦ 3/8 cover	50	48	52	48	38	37	39	53	44	48	42	48
	≦ 5/8 cover	76	76	81	72	65	62	63	77	68	70	70	76
	≦ 7/8 cover	90	91	95	37	84	80	81	90	89	88	88	91
Visibility: Percent of observations	< 2 miles	1	1	0	1	0	0	1	0	1	0	0	0
	< 5 miles	2	2	1	2	1	1	2	1	2	1	1	1

Median—Half the observations fall below and half above this point.
≦ Equal to or less than.
≧ Equal to or more than.
< Less than.

OCEAN AREA G

Months		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Pressure	¼ of obs. ≦	1011	1012	1012	1011	1011	1012	1012	1011	1010	1010	1010	1011
Sea level pressure	Median	1012	1013	1013	1012	1012	1012	1013	1012	1011	1011	1011	1012
(Millibars)	¼ of obs. ≧	1014	1015	1015	1013	1013	1014	1014	1013	1012	1012	1012	1013
Temperature, air (° F.)	¼ of obs. ≦	77	76	77	78	79	80	80	81	81	82	80	78
	Median	78	77	78	79	81	81	81	82	82	82	31	80
	¼ of obs. ≧	80	79	79	80	82	82	82	83	83	83	52	81
Temperature, mean sea surface (° F.)		80	79	79	80	81	82	82	83	84	83	83	81
Precipitation: Percent of observations with precipitation		11	3	4	4	4	8	8	8	11	9	8	7
Cloudiness: Percent of observations with	≦ 3/8 cover	45	50	52	42	41	31	34	41	40	41	39	48
	≦ 5/8 cover	72	78	78	71	68	62	63	70	69	72	70	72
	≦ 7/8 cover	90	92	93	92	88	83	84	89	89	90	90	88
Visibility: Percent of observations	< 2 miles	1	1	1	1	1	1	1	1	1	0	0	1
	< 5 miles	2	2	2	2	2	2	2	2	2	1	1	2

Median—Half the observations fall below and half above this point.
≦ Equal to or less than.
≧ Equal to or more than.
< less than.

TABLE I: From: H. O. 21

I.5 Winds

The following is of doubtful value to the design of an OTEC plant which must be designed to withstand hurricane-force winds and their effects (see Hurricanes), but it is included for completeness and for its use in considering the requirements of surface-supply vessels.

The proposed Yabucoa site falls within the climatological region of the easterly Trades, which in the Caribbean are relatively constant in speed and direction throughout the year (see Figure 6). The center of the Bermuda high moves slightly north in the summer, and south in winter so that the dominant wind direction at the site is easterly in spring and summer and NNE in autumn and winter. Windspeeds average from 9 to 10 knots in autumn to 12 to 15 knots in summer (H.O. 21) but the passage of fronts and easterly waves interrupts the normal Trade-wind pattern and strong northerly winds of greater than 28 knots may occur from November to April, with a frequency of about 2 % (SP189II). A diurnal variation is common in the Trades, with winds dropping at nightfall and increasing to a maximum in the afternoon. At Yabucoa this diurnal variation is accentuated by the landbreeze caused by the presence of the Puerto Rican landmass, with slight northerly winds being common during the night.

A crude graphic summary of oceanic wind conditions around the island of Puerto Rico is shown in Figures 7 - 10, drawn from data in SP-189II. More detailed data is available in SSMO Vol. 4.

I.6 Hurricanes

The majority of tropical cyclones in the Caribbean occur between the months of June and November inclusive. About 58% of these reach hurricane force (H.O. Pub. 21). In the five-degree square bounded by 15° - 20°N and 65° - 70°W, which includes the island of Puerto Rico, some 130 hurricanes may be expected within a one hundred year period (Figure 11). Typical hurricane tracks are shown in Figure 12. The expectancy of hurricanes within the site surveyed is naturally much less (about 13 in a hundred years), but sufficiently probable to warrant consideration since:

(i) Windspeeds may be in excess of 130 knots, with sustained speeds between 65 and 90 knots.

(ii) Waves as a result of these winds are characterized as "mountainous".

(iii) The surface of the sea is raised by up to one meter in the eye of the storm because of the locally lowered atmospheric pressure. This "dome" moves with the eye, producing the effect of a single wave between 25 and 500 n.m. long, travelling at about 12 knots.

(iv) Drastically lowered sea surface temperature caused by hurricanes, with noticeable effects to 500 meters. The isotherms rise sharply under the eye, as a result of the

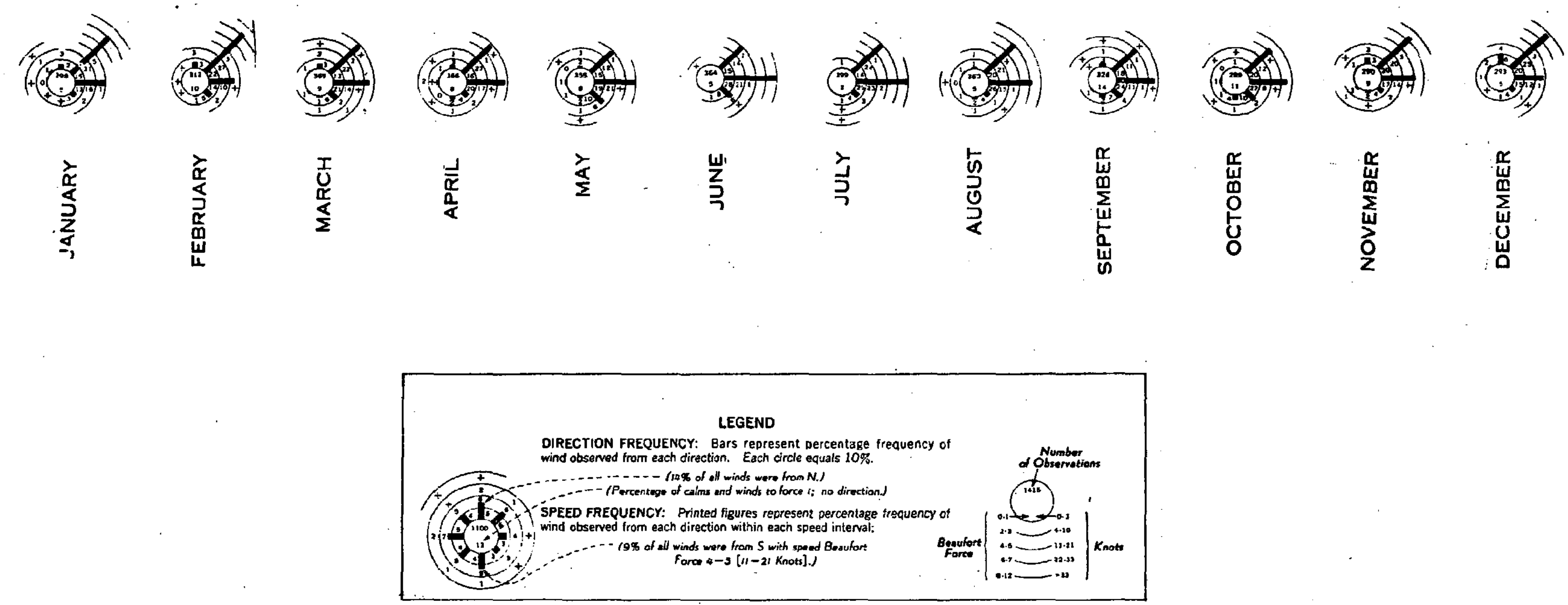


FIG. 6 WIND ROSES FOR MONA PASSAGE, WEST OF PUERTO RICO
From: H.O. 21

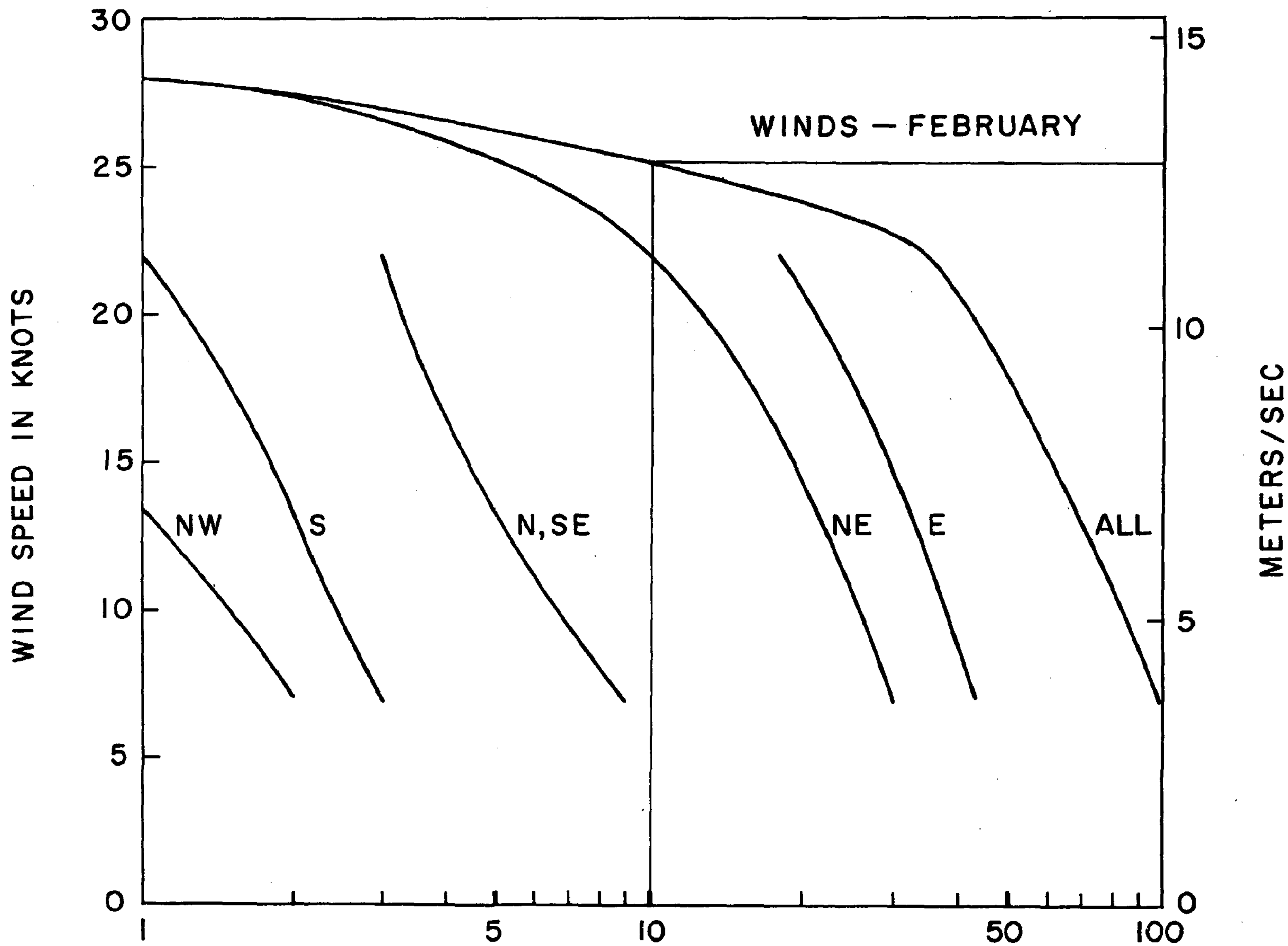


FIG. 7 PERCENT AS GREAT OR GREATER THAN
(10% of all winds have speeds greater than 13 m/s)

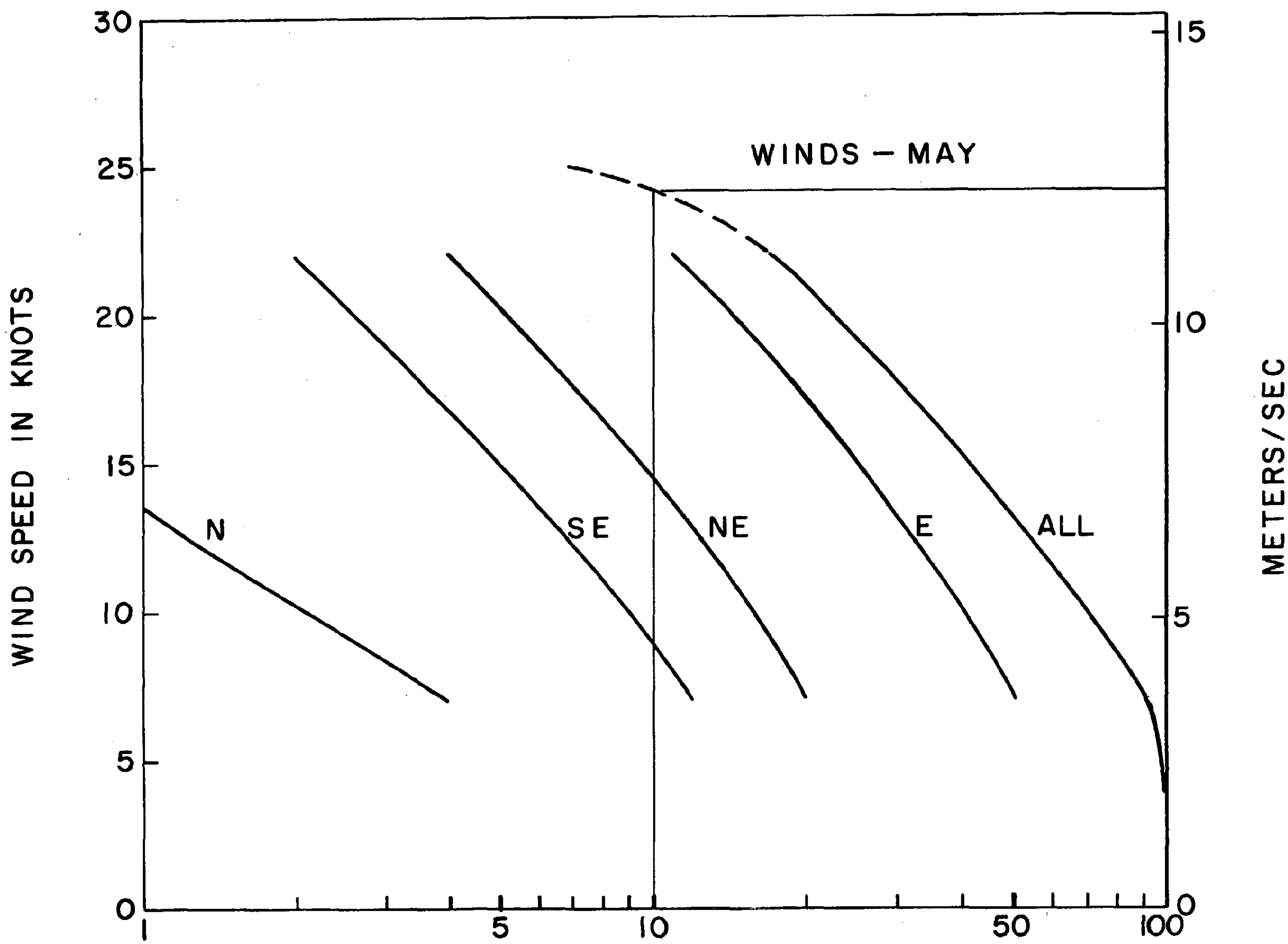


FIG. 8 PERCENT AS GREAT OR GREATER THAN
(10% of all winds have speeds greater than 12.5 m/s)

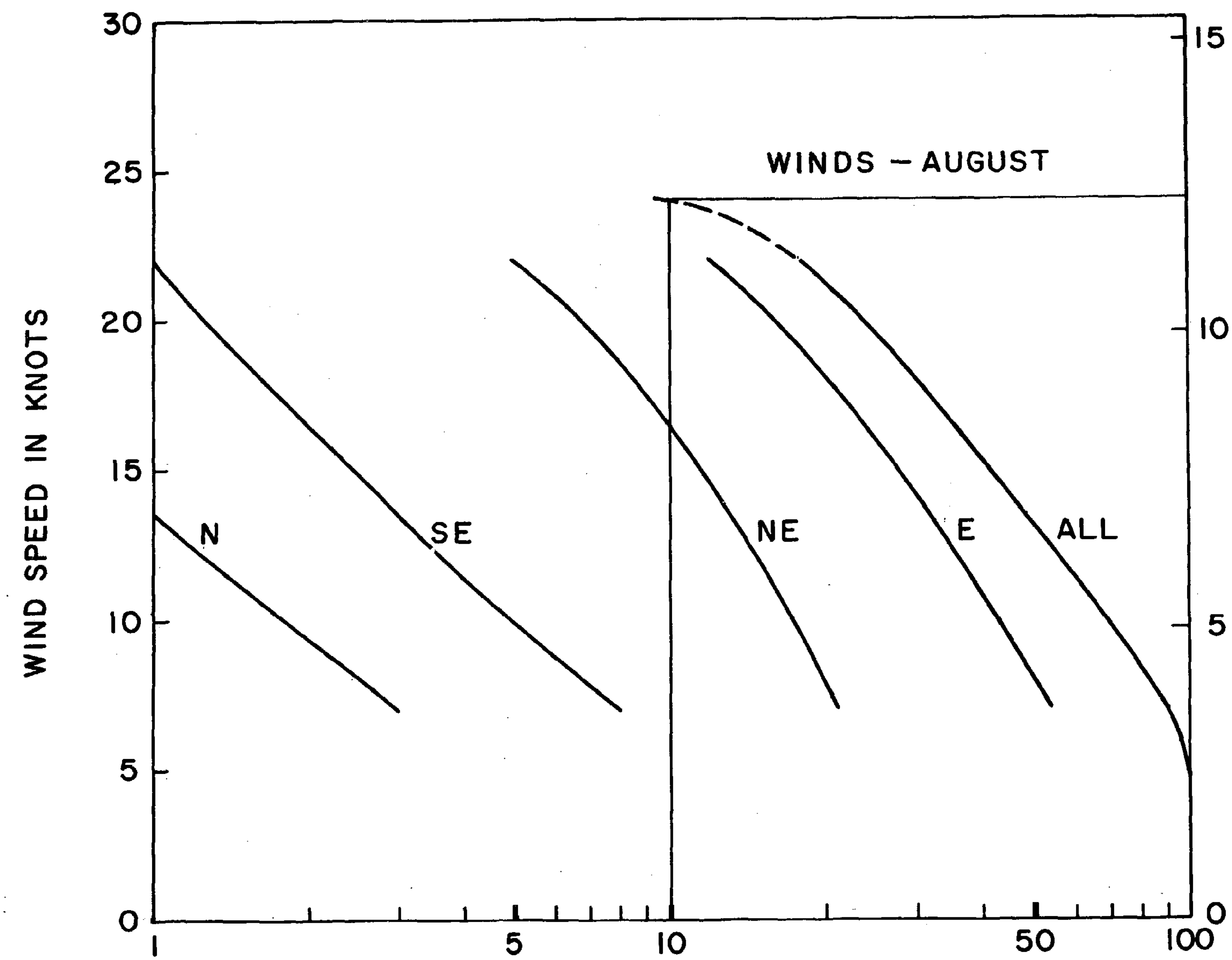


FIG. 9 PERCENT AS GREAT OR GREATER THAN
(10% of all winds have speeds greater than 12.3 m/s)

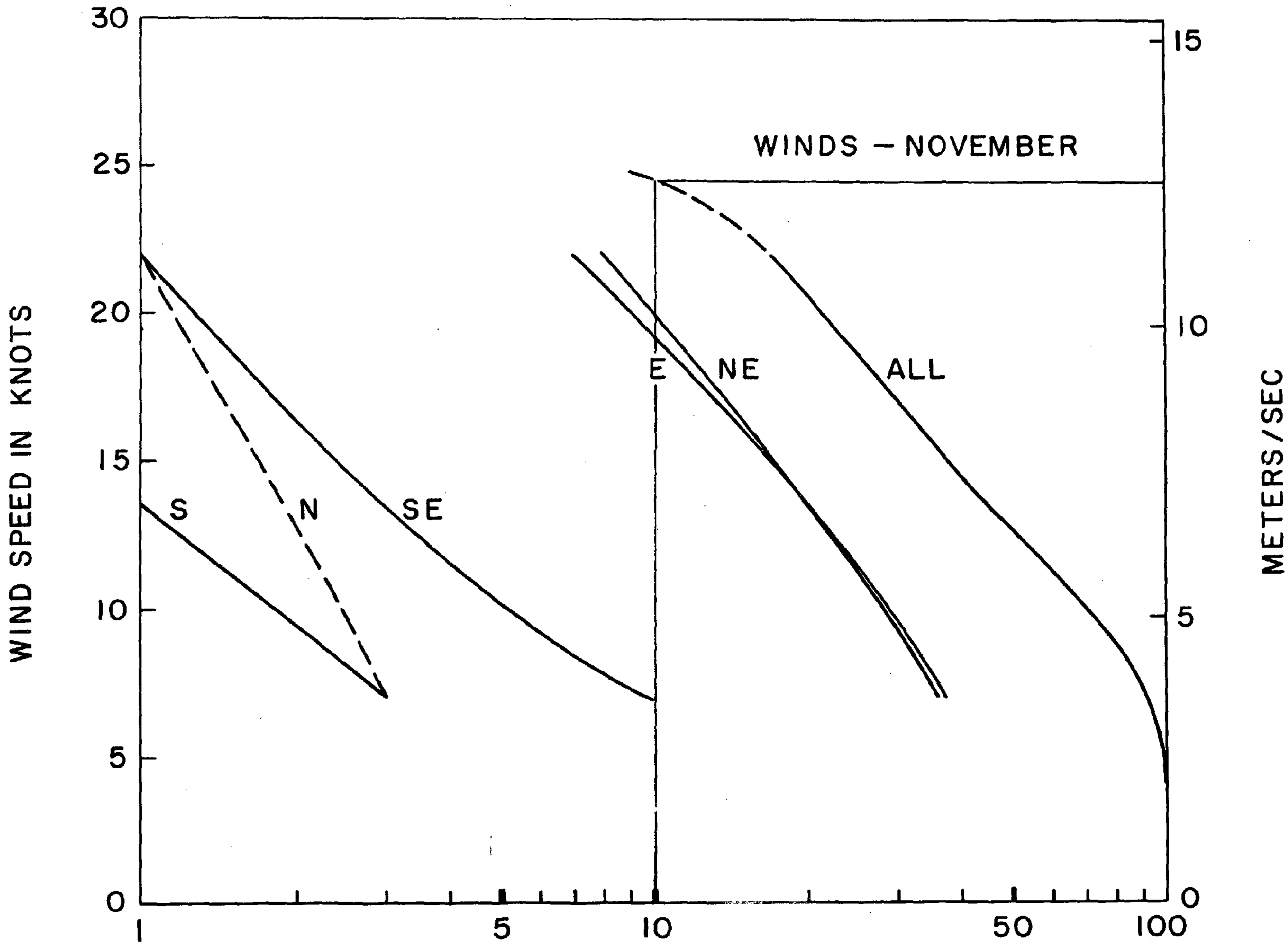
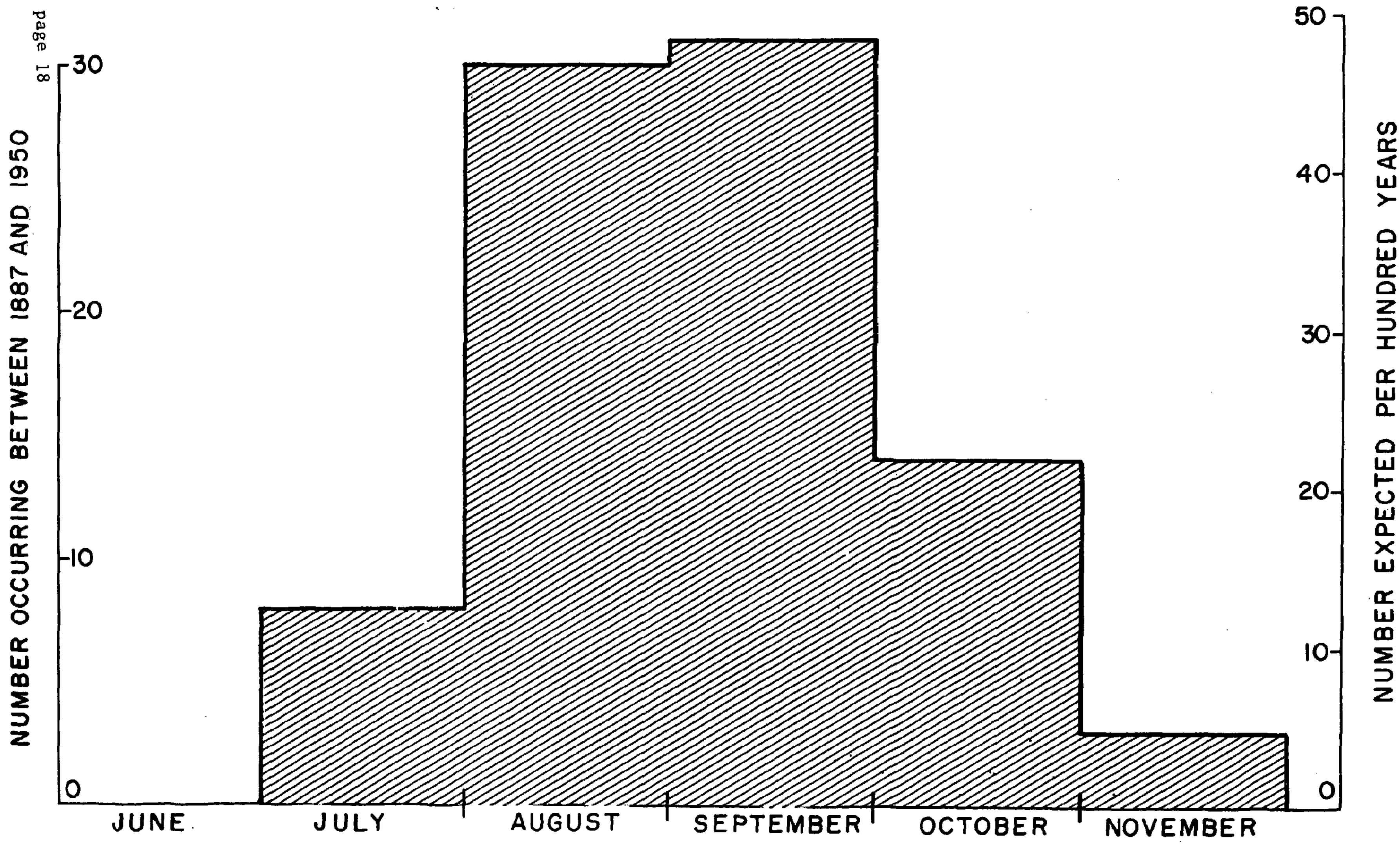


FIG. 10 PERCENT AS GREAT OR GREATER THAN
(10% of all winds have speeds greater than 12.5 m/s)

FIG. 11 OCCURRENCE OF TROPICAL CYCLONES IN THE FIVE DEGREE SQUARE BOUNDED BY 150°-20°N, 65°-70°W



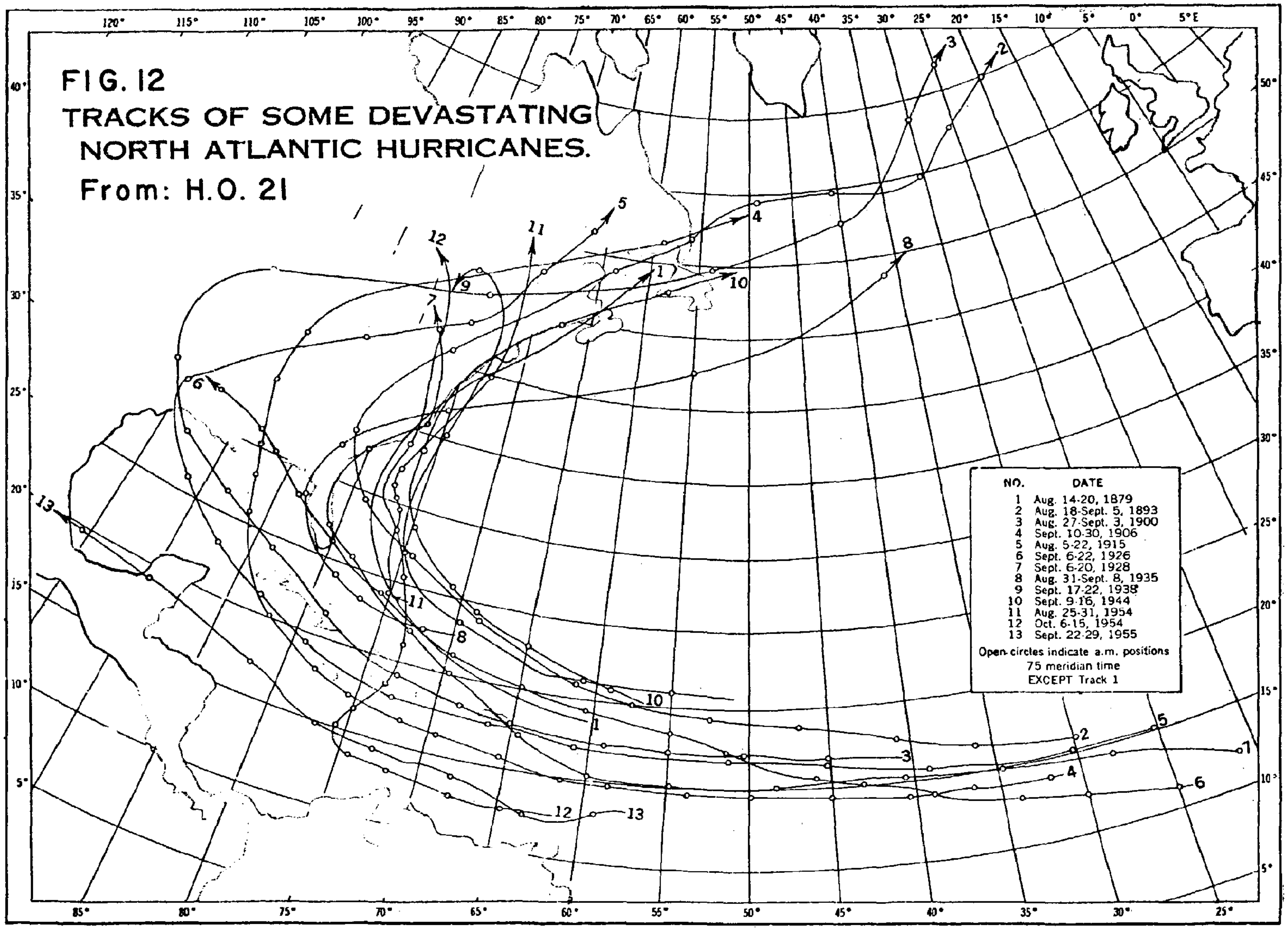


FIG. 12
TRACKS OF SOME DEVASTATING NORTH ATLANTIC HURRICANES.
From: H.O. 21

pressure imbalance and the oceanic divergence caused by the Ekman effect as the winds blow water away from the center. (See Figure 13).

I.7 Tides

The tidal cycle on the Caribbean coast of Puerto Rico is of the mixed diurnal type. The site is near the amphidromic (nodal) point of the principal lunar semi-diurnal (M_2) tidal constituent, which reduces the semi-diurnal contribution to tidal height. Figure 14 has been drawn from the 1974 Tide Tables produced by NOAA, for the coincidence of new moon and summer solstice to illustrate the maximum typical tidal range, which is about 55 cm. At the coast, therefore, the cause of major fluctuations is likely to be meteorological with run-up during storms. In deep water, both tidal and meteorological effects are minimized.

I.8 See and Swell

As the winds in the Caribbean near Puerto Rico shift from easterly in spring and summer to NNE in autumn and winter, so the oceanic wind-waves vary in direction (see Figures 15 - 18). Swell, however, has a dominantly easterly component all the year round. (See Figures 19 - 22). These figures were drawn from the data contained in SP189II for the oceanic region surrounding Puerto Rico and do not take into account the masking at Yabucoa by the islands of Puerto Rico and Vieques. The information is included for its value as a guide to the conditions which may be expected while the plant is being towed to the site from its place of construction.

A noticeable amelioration of conditions is found along the southern coasts of the Greater Antilles. Table II has been taken from H.O. 21, and refers to the south exposure of the islands of Jamaica, Cuba, Hispaniola and Puerto Rico.

The percentage of "calm" swell is over 85% for winter and summer in coastal waters and less than 19% in the open ocean. Similarly, swell in the coastal area is never observed in the quadrant N to E (0° to 90°) but in the open ocean this quadrant accounts for over two-thirds of all observed swell, and nearly all observations greater than 12 feet high (3.6 meters).

Very detailed monthly averages for the south of Puerto Rico are contained in "Summary of Synoptic Meteorological Observations", Volume 4, published by the U.S. Naval Weather Service Command in 1974. The region covered by this Summary overlaps Puerto Rico to the east and west, protruding into the Mona Passage and to the Virgin Islands. The averages, therefore, more closely resemble those for the oceanic regions of SP189II than those in the table above.

Note should be taken of the relatively frequent passage of hurricanes

SCHEMATIC REPRESENTATION OF DOMING CAUSED BY A HURRICANE

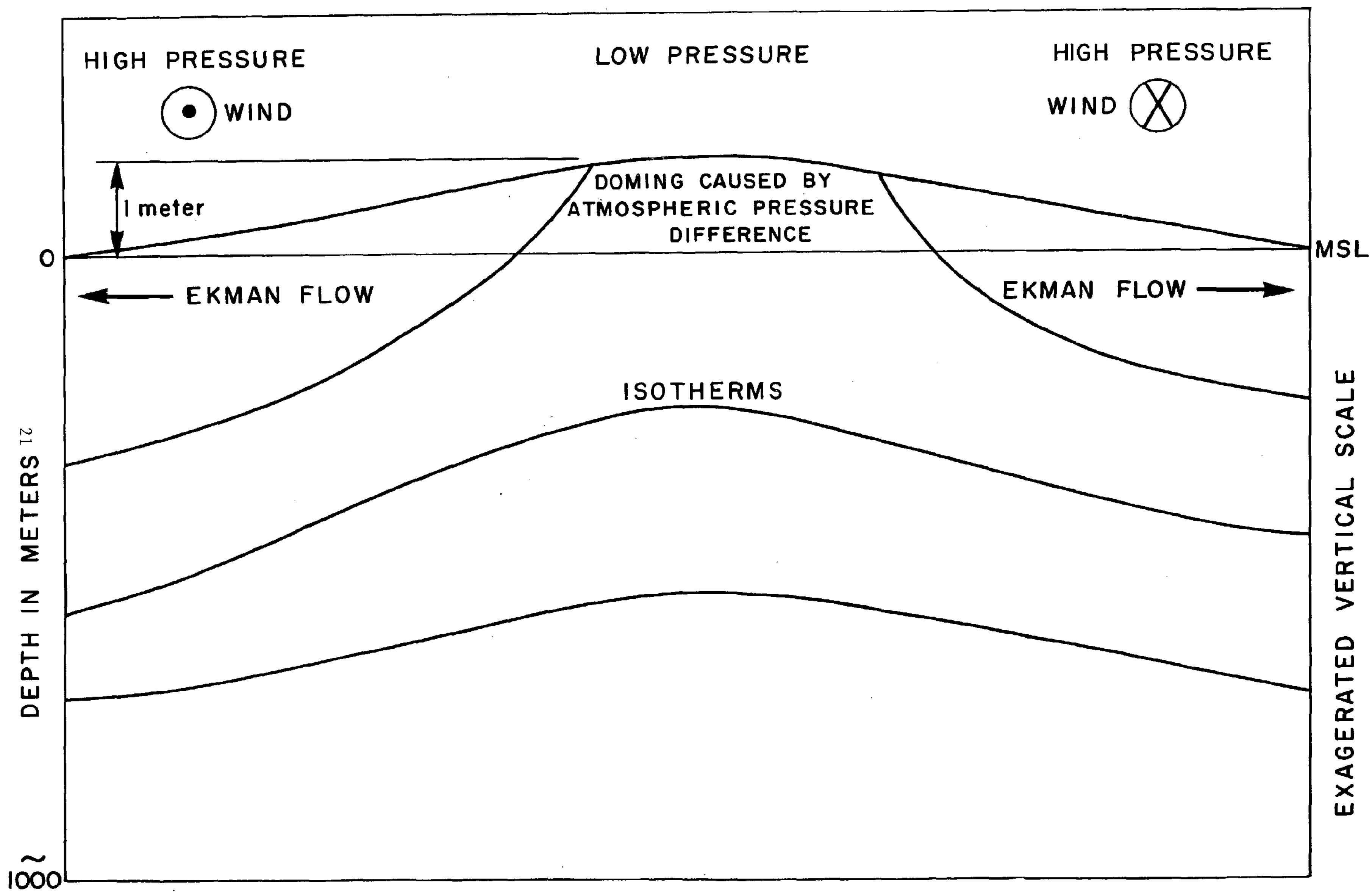


FIG. 13

PREDICTED TIDE FOR PUERTO MAUNABO, 15-24 JUNE, 1974 (GMT)

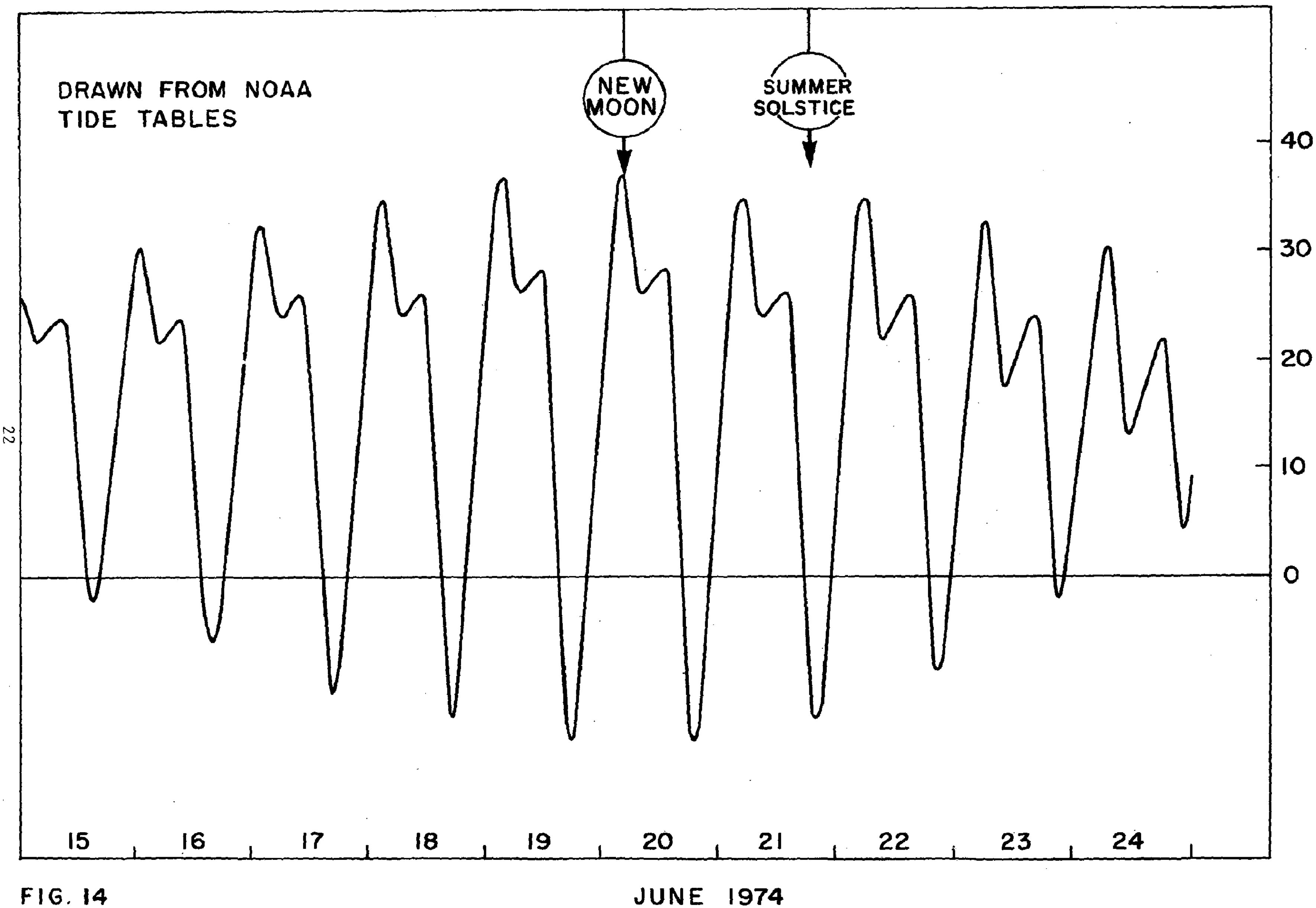
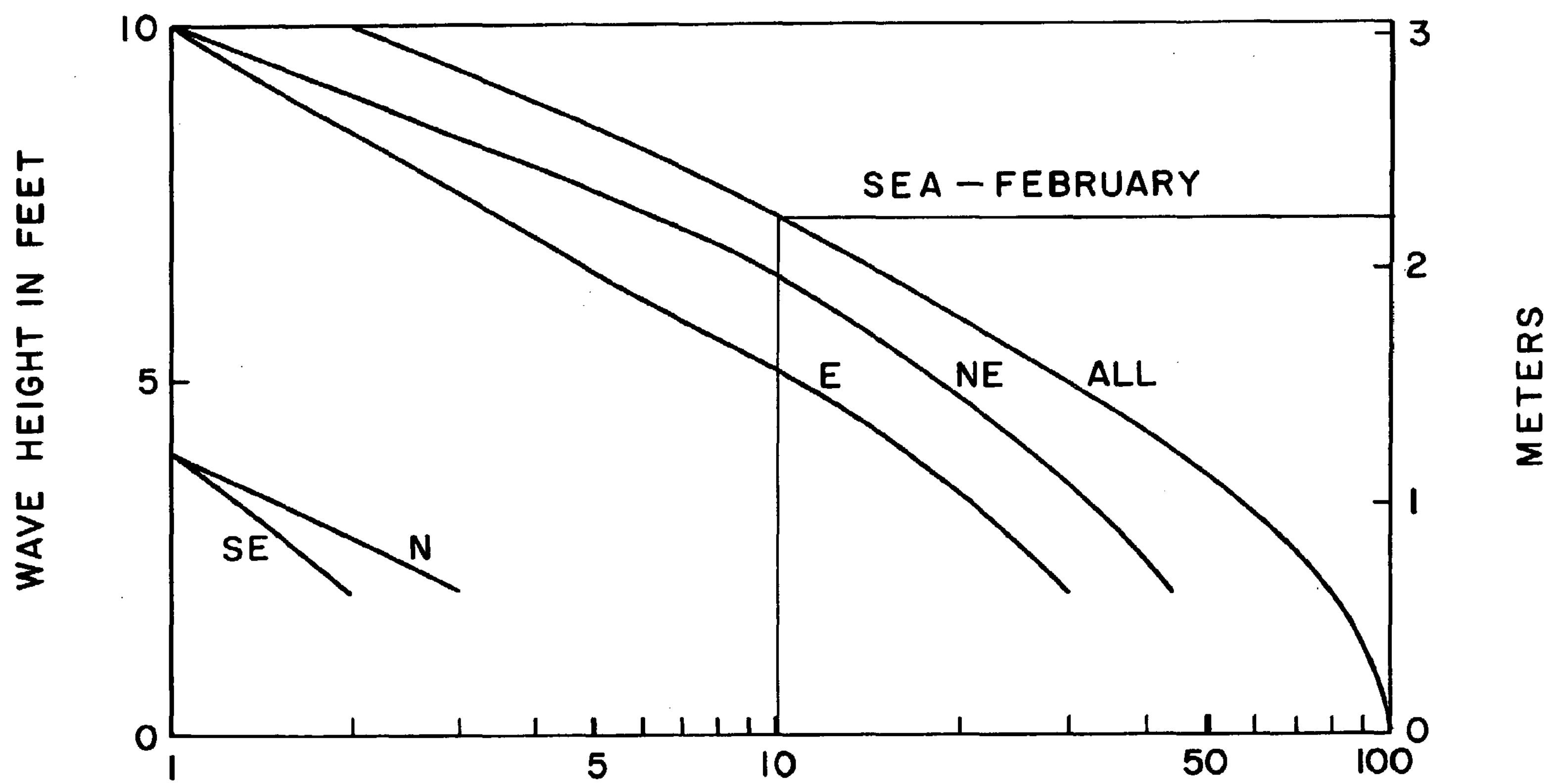


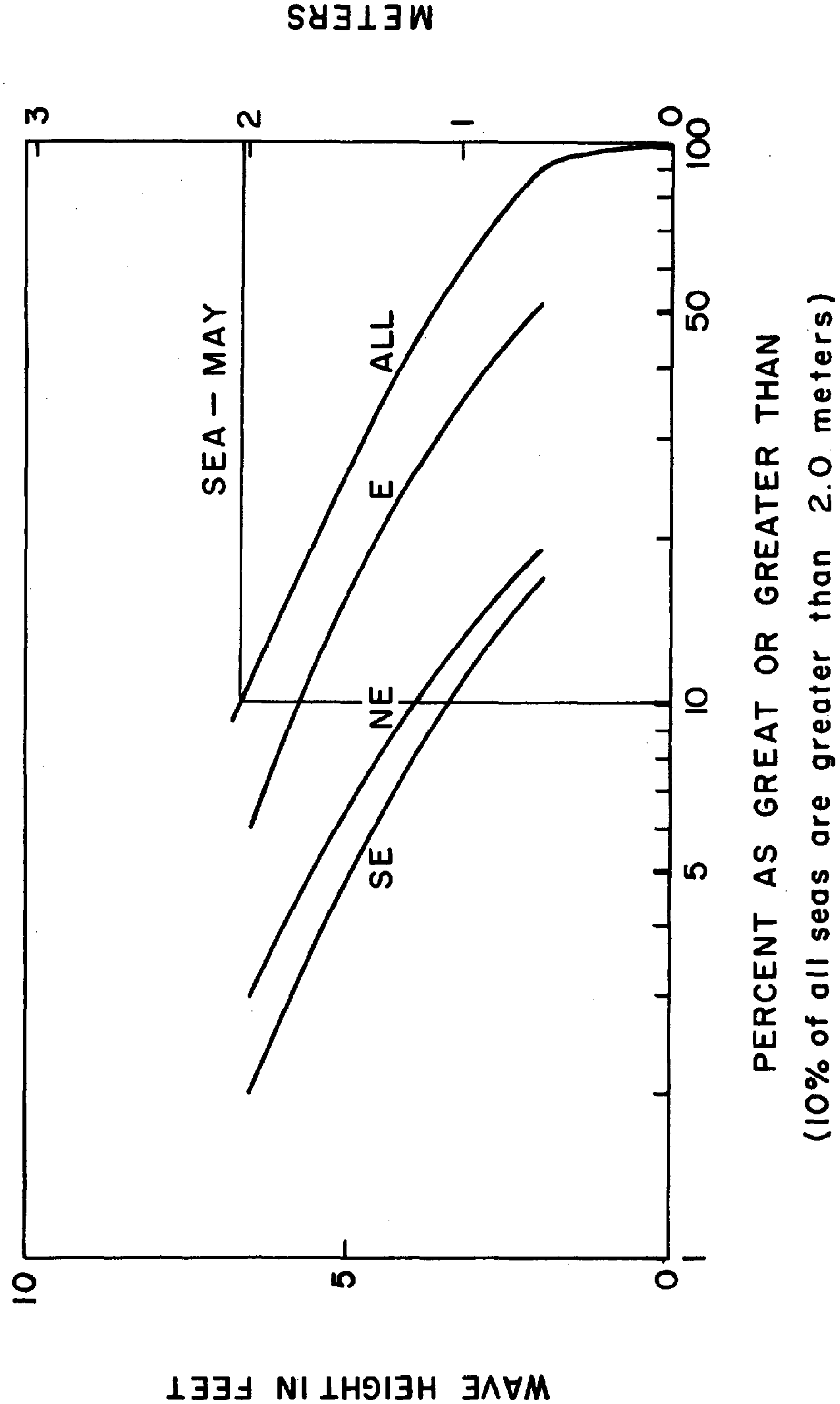
FIG. 14

FIG. 15



PERCENT AS GREAT OR GREATER THAN
(10% of all seas are greater than 2.2 meters)

FIG. 16



METERS
3
2
1
0
SEA — MAY
ALL
E
NE
SE
10
5
0
100
50
10
5
WAVE HEIGHT IN FEET
PERCENT AS GREAT OR GREATER THAN
(10% of all seas are greater than 2.0 meters)

FIG. 17

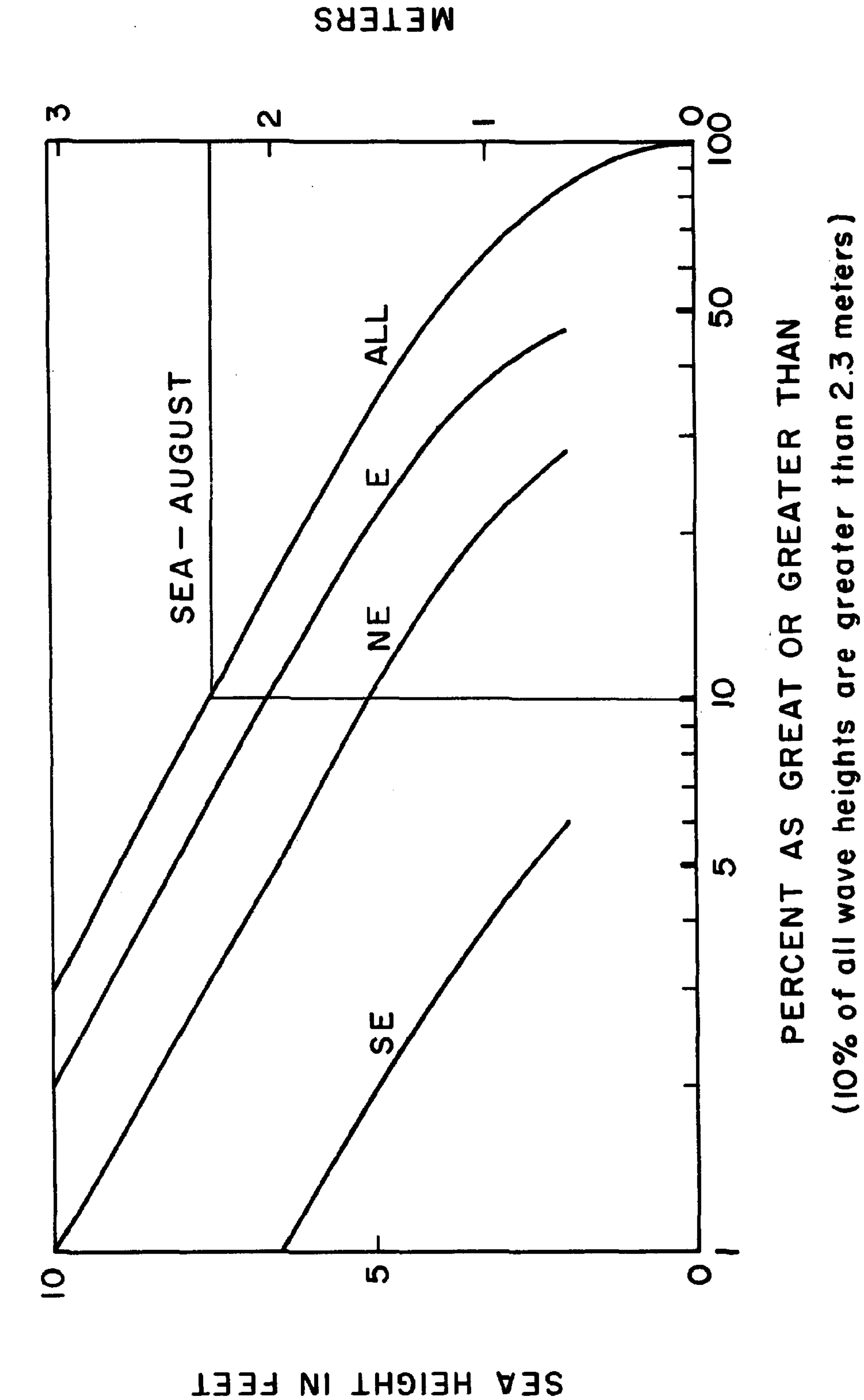

SEA - AUGUST
ALL
E
NE
SE
METERS
SEA HEIGHT IN FEET
PERCENT AS GREAT OR GREATER THAN
(10% of all wave heights are greater than 2.3 meters)
0
1
2
3
5
10
50
100

FIG. 18

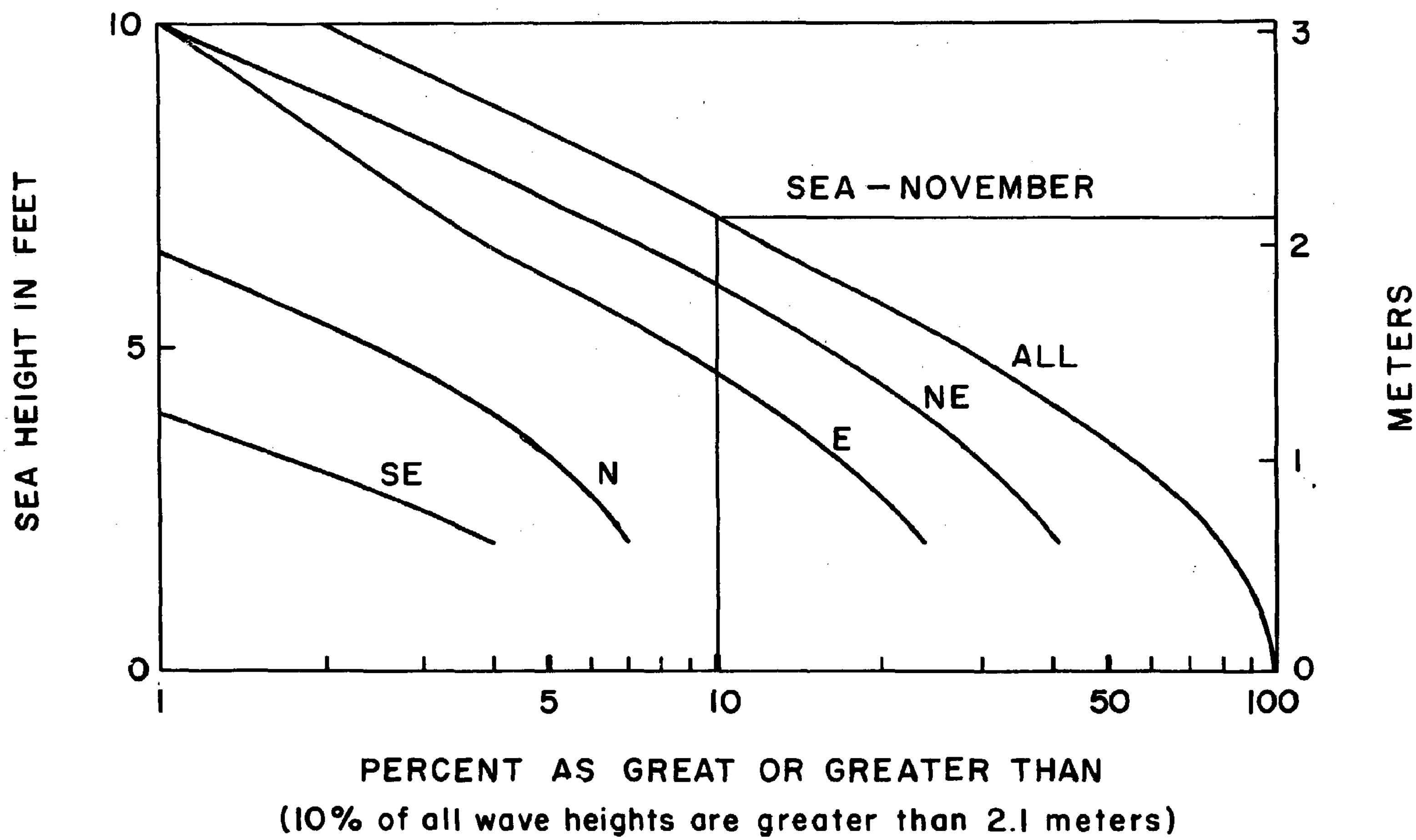

SEA HEIGHT IN FEET
METERS
SEA — NOVEMBER
ALL
NE
E
N
SE
10
5
0
3
2
1
0
1
5
10
50
100
PERCENT AS GREAT OR GREATER THAN
(10% of all wave heights are greater than 2.1 meters)

FIG. 19

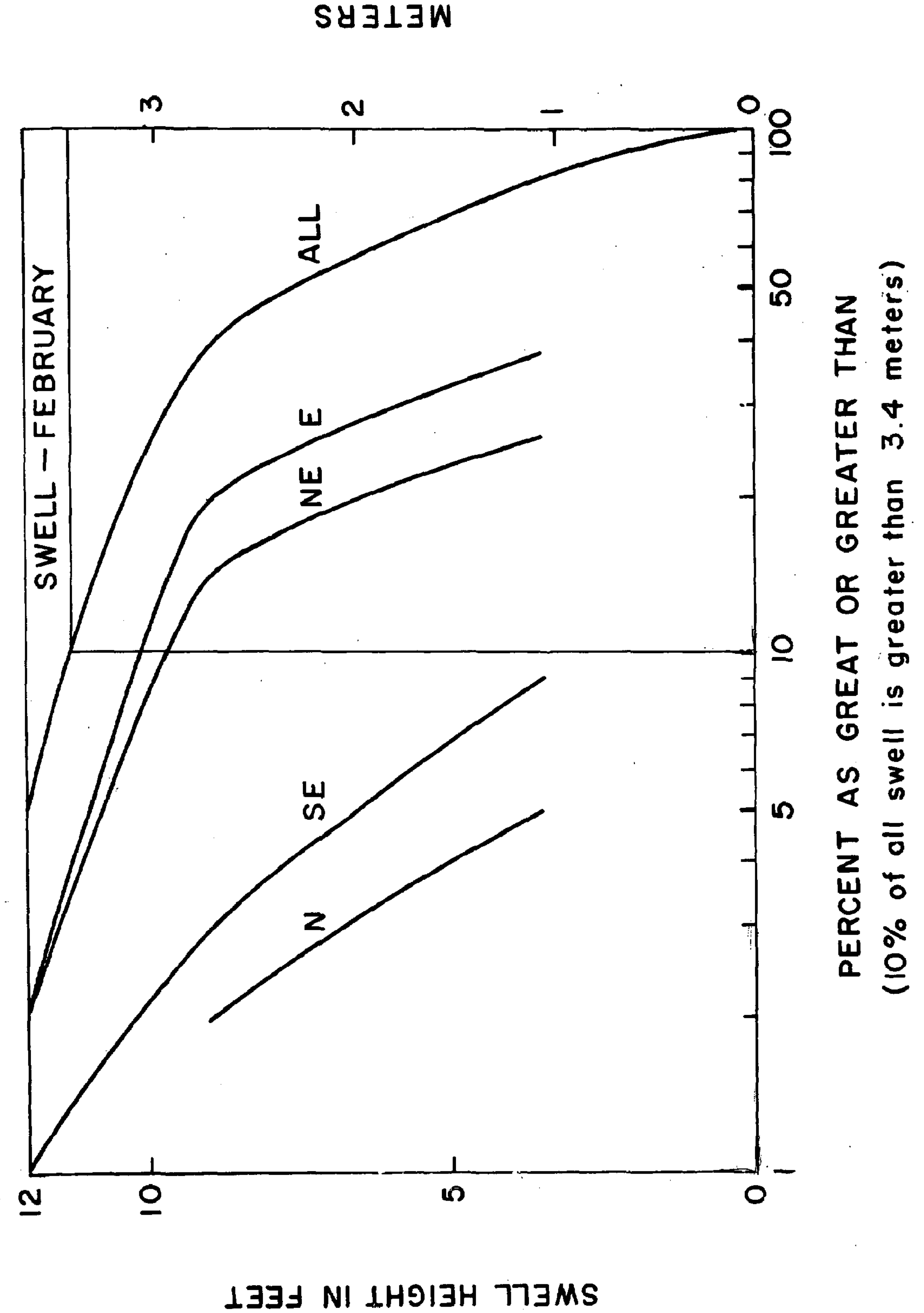
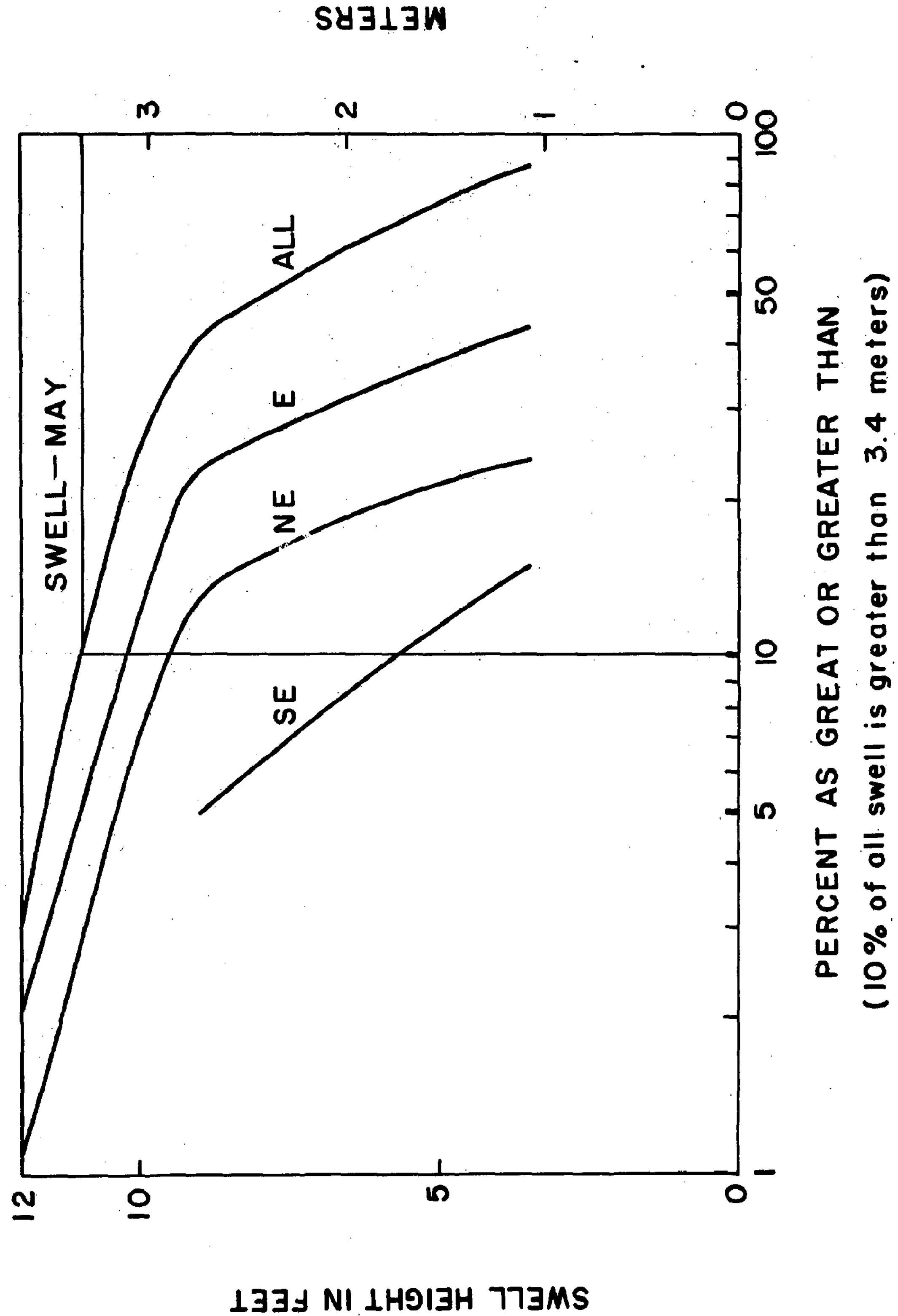

SWELL — FEBRUARY
METERS
SWELL HEIGHT IN FEET
PERCENT AS GREAT OR GREATER THAN
(10% of all swell is greater than 3.4 meters)
ALL
NE
E
SE
N

FIG. 20



SWELL—MAY
ALL
E
NE
SE
METERS
3
2
1
0
SWELL HEIGHT IN FEET
12
10
5
0
1
5
10
50
100
PERCENT AS GREAT OR GREATER THAN
(10% of all swell is greater than 3.4 meters)

FIG. 21

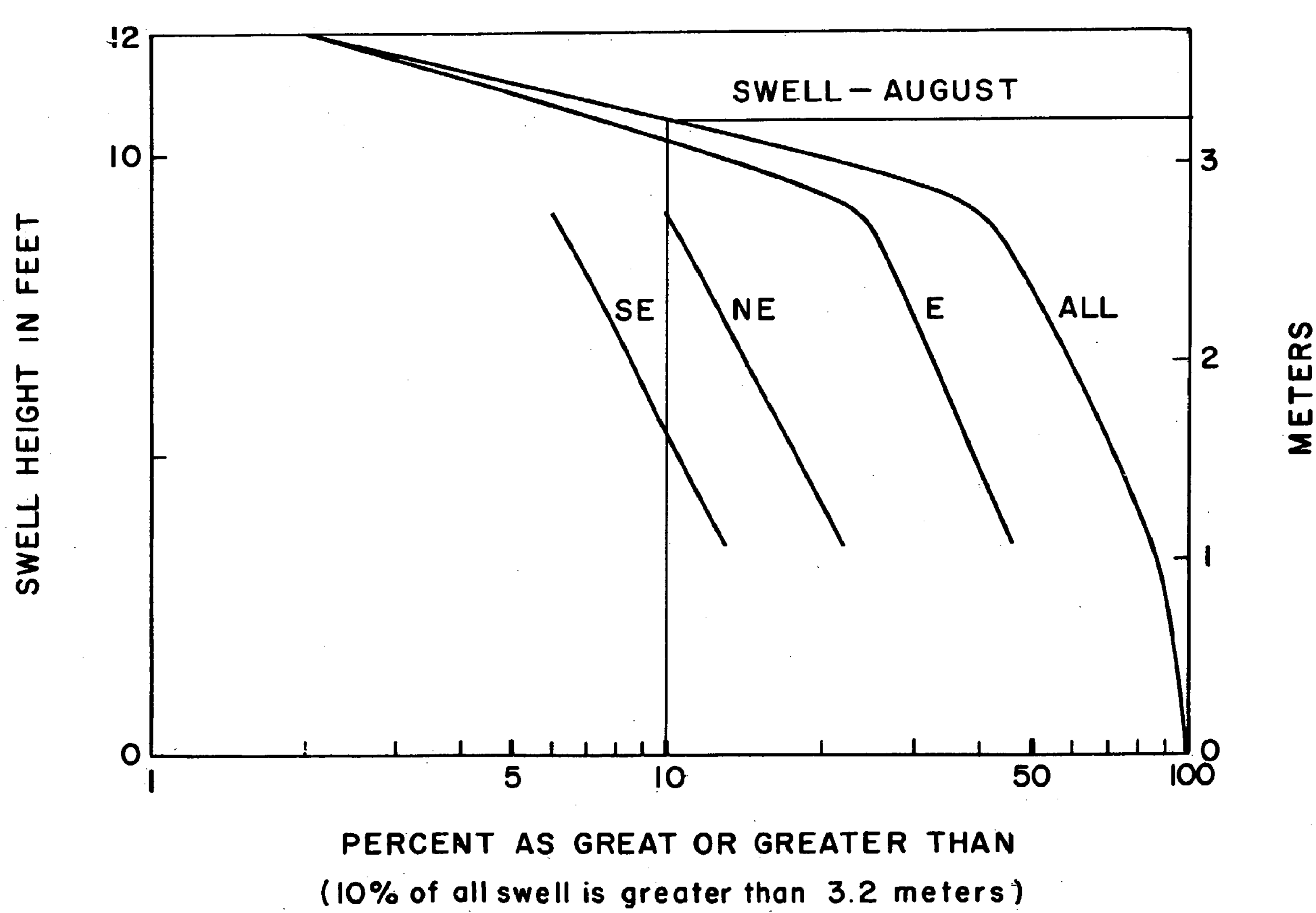
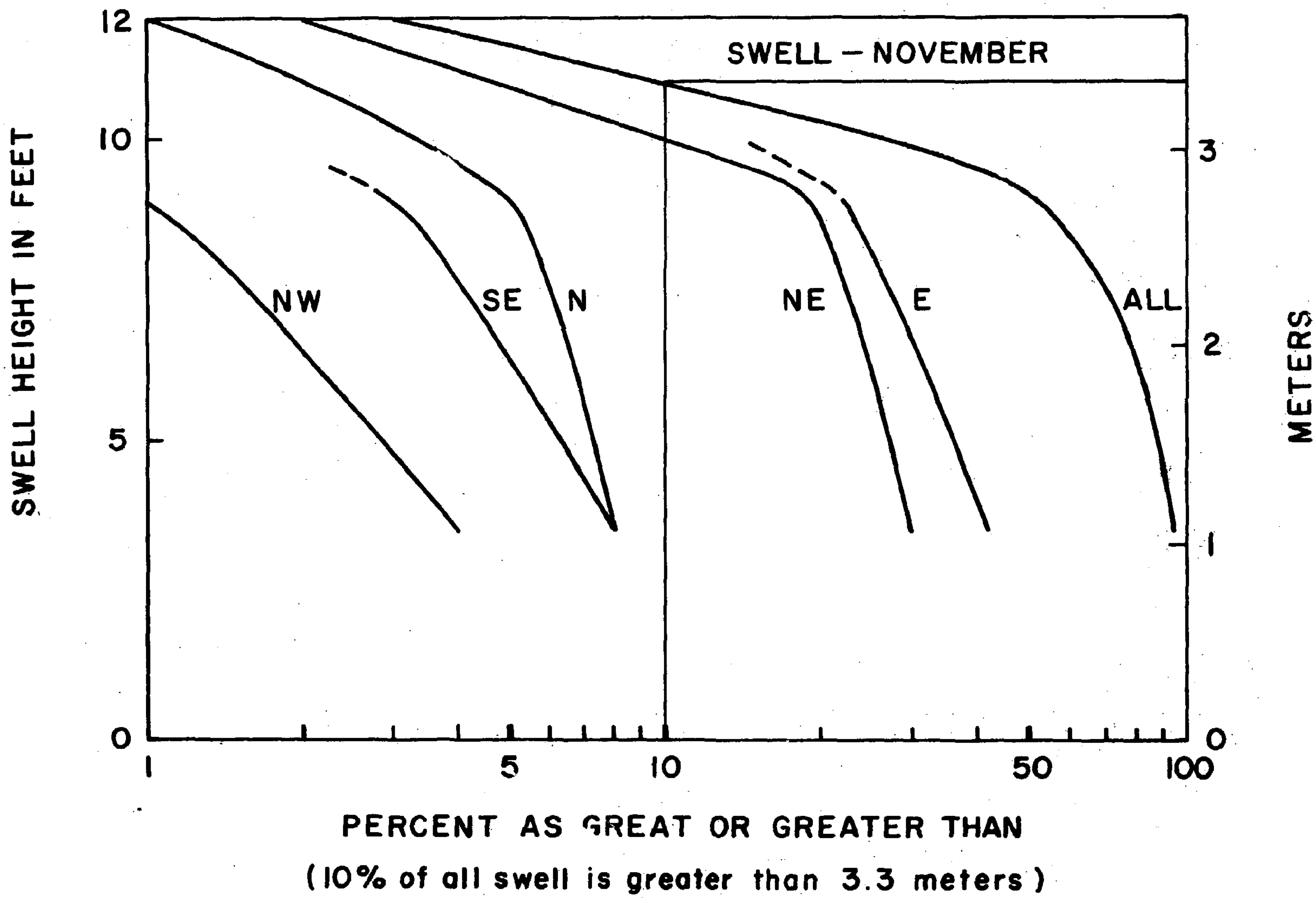
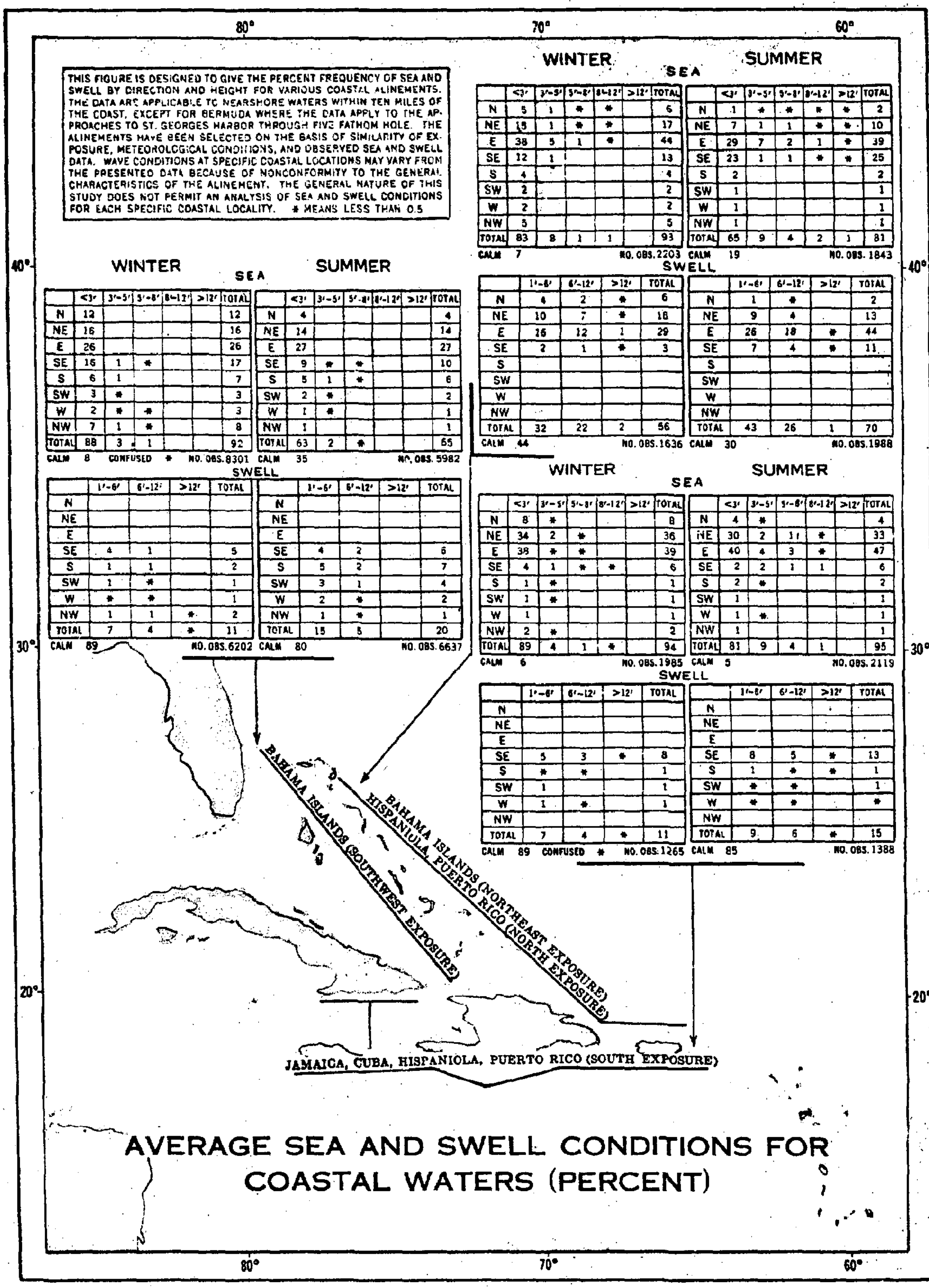

SWELL — AUGUST
SE
NE
E
ALL
12
10
0
SWELL HEIGHT IN FEET
3
2
1
0
METERS
1
5
10
50
100
PERCENT AS GREAT OR GREATER THAN
(10% of all swell is greater than 3.2 meters)

FIG. 22



SWELL – NOVEMBER
SWELL HEIGHT IN FEET
METERS
12
10
5
0
3
2
1
0
NW
SE
N
NE
E
ALL
1
5
10
50
100
PERCENT AS GREAT OR GREATER THAN
(10% of all swell is greater than 3.3 meters)



THIS FIGURE IS DESIGNED TO GIVE THE PERCENT FREQUENCY OF SEA AND SWELL BY DIRECTION AND HEIGHT FOR VARIOUS COASTAL ALINEMENTS. THE DATA ARE APPLICABLE TO NEARSHORE WATERS WITHIN TEN MILES OF THE COAST, EXCEPT FOR BERMUDA WHERE THE DATA APPLY TO THE APPROACHES TO ST. GEORGES HARBOR THROUGH FIVE FATHOM HOLE. THE ALINEMENTS HAVE BEEN SELECTED ON THE BASIS OF SIMILARITY OF EXPOSURE, METEOROLOGICAL CONDITIONS, AND OBSERVED SEA AND SWELL DATA. WAVE CONDITIONS AT SPECIFIC COASTAL LOCATIONS MAY VARY FROM THE PRESENTED DATA BECAUSE OF NONCONFORMITY TO THE GENERAL CHARACTERISTICS OF THE ALINEMENT. THE GENERAL NATURE OF THIS STUDY DOES NOT PERMIT AN ANALYSIS OF SEA AND SWELL CONDITIONS FOR EACH SPECIFIC COASTAL LOCALITY. * MEANS LESS THAN 0.5

WINTER — SEA — SUMMER

	<3'	3'-5'	5'-8'	8'-12'	>12'	TOTAL
N	5	1	*	*		6
NE	15	1	*	*		17
E	38	5	1	*		44
SE	12	1				13
S	4					4
SW	2					2
W	2					2
NW	5					5
TOTAL	83	8	1	1		93

CALM 7 NO. OBS. 2203

	<3'	3'-5'	5'-8'	8'-12'	>12'	TOTAL
N	1	*	*	*	*	2
NE	7	1	1	*	*	10
E	29	7	2	1	*	39
SE	23	1	1	*	*	25
S	2					2
SW	1					1
W	1					1
NW	1					1
TOTAL	65	9	4	2	1	81

CALM 19 NO. OBS. 1843

SWELL

	1'-6'	6'-12'	>12'	TOTAL
N	4	2	*	6
NE	10	7	*	18
E	16	12	1	29
SE	2	1	*	3
S				
SW				
W				
NW				
TOTAL	32	22	2	56

CALM 44 NO. OBS. 1636

	1'-6'	6'-12'	>12'	TOTAL
N	1	*		2
NE	9	4		13
E	26	18	*	44
SE	7	4	*	11
S				
SW				
W				
NW				
TOTAL	43	26	1	70

CALM 30 NO. OBS. 1988

WINTER — SEA — SUMMER

	<3'	3'-5'	5'-8'	8'-12'	>12'	TOTAL
N	12					12
NE	16					16
E	26					26
SE	16	1	*			17
S	6	1				7
SW	3	*				3
W	2	*	*			3
NW	7	1	*			8
TOTAL	88	3	1			92

CALM 8 CONFUSED * NO. OBS. 8301

	<3'	3'-5'	5'-8'	8'-12'	>12'	TOTAL
N	4					4
NE	14					14
E	27					27
SE	9	*	*			10
S	5	1	*			6
SW	2	*				2
W	1	*				1
NW	1					1
TOTAL	63	2	*			65

CALM 35 NO. OBS. 5982

SWELL

	1'-6'	6'-12'	>12'	TOTAL
N				
NE				
E				
SE	4	1		5
S	1	1		2
SW	1	*		1
W	*	*		1
NW	1	1	*	2
TOTAL	7	4	*	11

CALM 89 NO. OBS. 6202

	1'-6'	6'-12'	>12'	TOTAL
N				
NE				
E				
SE	4	2		6
S	5	2		7
SW	3	1		4
W	2	*		2
NW	1	*		1
TOTAL	15	5		20

CALM 80 NO. OBS. 6637

WINTER — SEA — SUMMER

	<3'	3'-5'	5'-8'	8'-12'	>12'	TOTAL
N	8	*				8
NE	34	2	*			36
E	38	*	*			39
SE	4	1	*	*		6
S	1	*				1
SW	1	*				1
W	1					1
NW	2	*				2
TOTAL	89	4	1	*		94

CALM 6 NO. OBS. 1985

	<3'	3'-5'	5'-8'	8'-12'	>12'	TOTAL
N	4	*				4
NE	30	2	1	*		33
E	40	4	3	*		47
SE	2	2	1	1		6
S	2	*				2
SW	1					1
W	1	*				1
NW	1					1
TOTAL	81	9	4	1		95

CALM 5 NO. OBS. 2119

SWELL

	1'-6'	6'-12'	>12'	TOTAL
N				
NE				
E				
SE	5	3	*	8
S	*	*		1
SW	1			1
W	1	*		1
NW				
TOTAL	7	4	*	11

CALM 89 CONFUSED * NO. OBS. 1265

	1'-6'	6'-12'	>12'	TOTAL
N				
NE				
E				
SE	8	5	*	13
S	1	*	*	1
SW	*	*		1
W	*	*		*
NW				
TOTAL	9	6	*	15

CALM 85 NO. OBS. 1388

AVERAGE SEA AND SWELL CONDITIONS FOR COASTAL WATERS (PERCENT)

TABLE II: From: H. O. 21

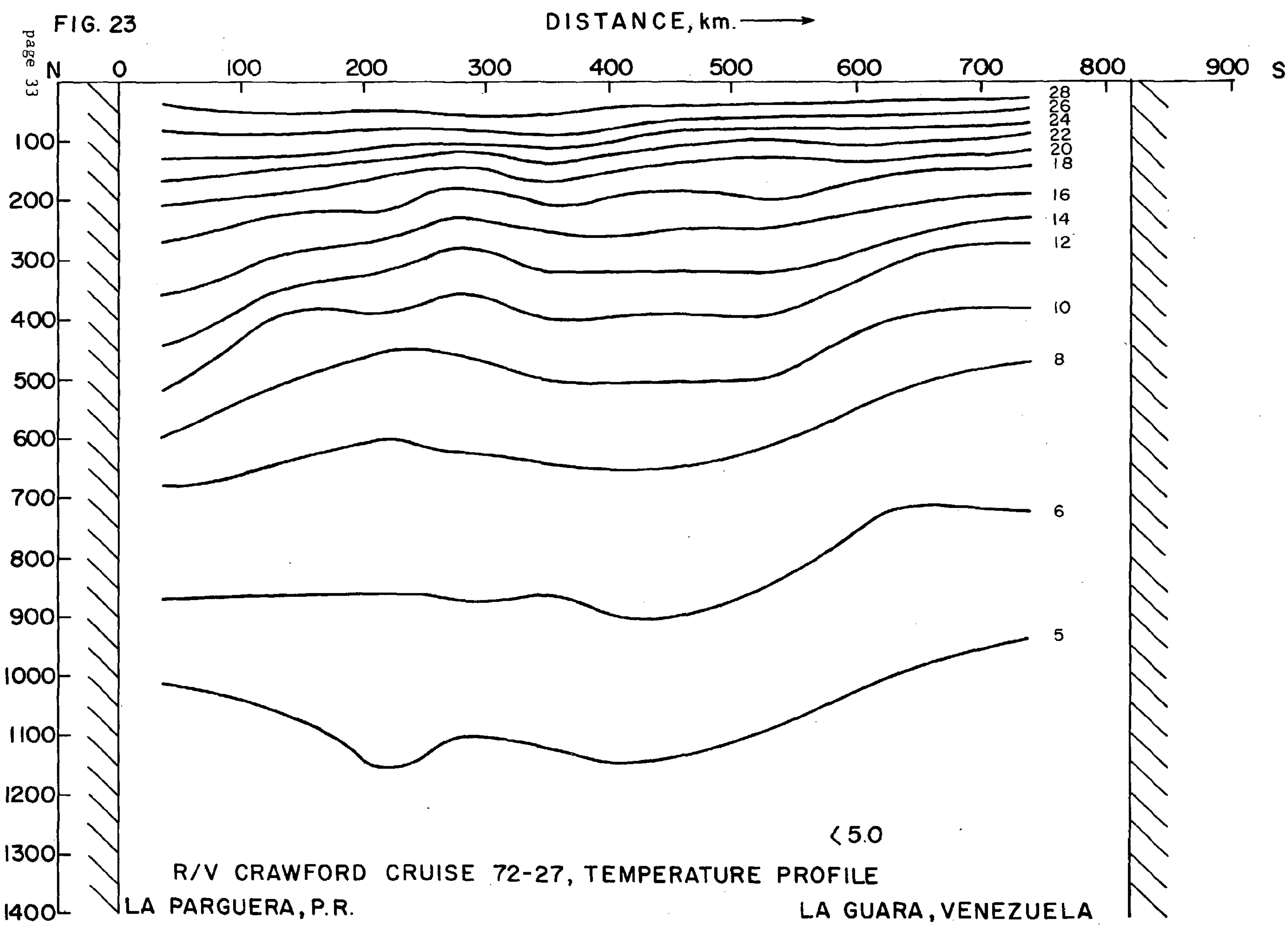
through the region (see Hurricanes, section I.6). Resultant seas are not listed in these averages and reliable estimates of wave height are still being sought.

The plant should be designed to withstand hurricanes on the site. Depending on the place where the plant is built, the safest approach for the tow to the site is along the southern coasts of the Greater Antilles.

I.9 Water Masses

A floating OTEC plant 1000 meters long will pass through four different water masses which have vastly different origins and properties which need to be considered. From the surface to about 100 meters the Tropical Surface Water is found with high temperatures (25° - 29°C) and salinities between 33 °/₀₀ and 36 °/₀₀ but usually less than 35.5 °/₀₀. This water mass has its origin in the tropical rain belt under the equatorial atmospheric trough. The salinity is also somewhat decreased by river run-off from the Amazon and Orinoco Rivers before the North Equatorial Current passes the Lesser Antilles to become the Caribbean Current. The warm water wedge of Tropical Surface Water (TSW) attains its greatest thickness (about 100 meters) along the coasts of the Greater Antilles because of the geostrophic tilt of the isotherms as the Caribbean Current moves westwards. Figure 23, a temperature section along 67°W from Puerto Rico to Venezuela, illustrates this wedging effect. The 20°C isotherm is 210 meters below the surface at Puerto Rico, but only 120 meters at Venezuela. Beneath the TSW, between 100 to 200 meters, is found the Subtropical Underwater, which has its origin beneath the Bermuda atmospheric high. This water mass is more constant in character, varying only about 20° - 24°C and 36.8 °/₀₀ - 37.2 °/₀₀. A large density difference is found between these upper two water masses, maintaining them essentially separate and retarding mixing despite their contiguity. (See Density, section I.12). At depths of 600 - 800 meters the Antarctic Intermediate Water is found, which is characteristically 6° - 7° C, 34.8 °/₀₀. At 1000 meters the influence of the North Atlantic Deep Water (NADW) which flows into the basin over the Anegada/Jungfern Sill is seen with temperatures of 4° - 5°C, and salinities very near 35 °/₀₀. This last water mass extends to the bottom in the Venezuela Basin, and is over 3000 meters thick in parts. Since it is somewhat different than NADW, e.g., in silicate content, it is more aptly called Venezuela Bottom Water (VBW). A rough estimate of the amount of this deep water in the Venezuela Basin alone is in excess of 150,000 cubic kilometers. These water masses are most easily identified by their characteristic temperatures and salinities on a Temperature - Salinity (T - S °/₀₀) plot (Figure 24) which oceanographers find convenient for water mass analysis. However, this type of plot does <u>not</u> show the relative proportions, nor the absolute amounts of water present and should be interpreted accordingly.

FIG. 23


DISTANCE, km.
N
0
100
200
300
400
500
600
700
800
900
S
28
26
24
22
20
18
16
14
12
10
8
6
5
1000
1100
1200
1300
1400
<5.0
R/V CRAWFORD CRUISE 72-27, TEMPERATURE PROFILE
LA PARGUERA, P.R.
LA GUARA, VENEZUELA

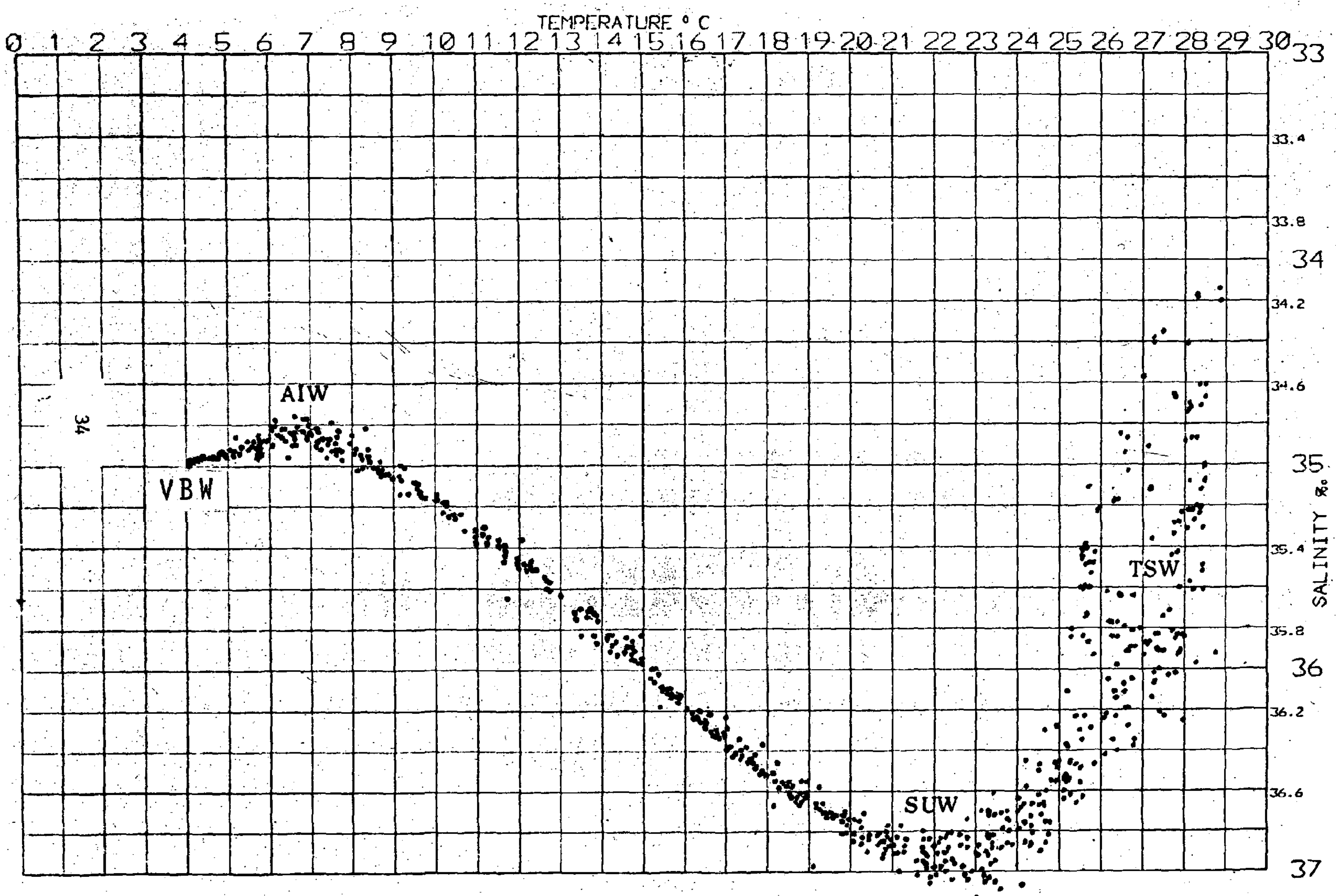


FIG. 24

TS PLOT FOR STA.

2739
2747
25920
2593
2594
2595
2600
2601
2609
2610
2611
2620
2621
2630
2632
2645
2652
2660
2661
2662
2670
2677
2700
2701
2712
2713
2714
430
32
33
34
2715
2716
2717
2725
2726
2727
2728

I.10 Temperatures

The strong westward-flowing Caribbean Current causes a geostrophic tilt of the isotherms, so that a wedge of warm water is always found in the northern part of the Caribbean Sea (Figure 23). Large temperature differences with depth are therefore found along the south coast of Puerto Rico. Figure 25 shows the variation of in situ temperature with depth at the PESCA serial station at 17°38' N, 67° W. The wedge of warm surface water, the sharpness of the thermocline and the relatively invariant temperatures at depths greater than 750 meters stand out well. Surface temperatures vary about 3.5 °, but at 1000 meters the variation is less than 1° C. By using the mean surface temperature as a reference, an estimate of the mean temperature difference between the surface and any depth can be derived from the lower abcissa of the figure. In this and the next diagram the slight adiabatic cooling (about 0.01°/ per 100 meters) which occurs when water at depth is brought to the surface has been ignored.

Figure 26 has been drawn from the same data to illustrate the variation with time of temperature at a single position. The 25° C isotherm lies at about 100 meters, with small deviations. This ensures a thick warm surface layer which is accentuated in the summer months by an increase in temperature of the water above 100 meters to as much as 29°C. This warming is not the result of local insolation alone, but is general for the Caribbean. The variations in depth of the 15°C isotherm may be due to reversals in the current. The temperature difference between the surface and 1000 meters has been extracted, and is presented as a time-dependent variable, showing that this difference is never less than 20.3° C, and can exceed 23° C.

I.11 Salinity

Figure 27 shows the variability of salinity with depth at the PESCA serial station. Surface waters show a wide variation (34.2 °/oo to 36.2 °/oo) due to seasonal effects associated with precipitation and discharge from large South American river systems (Amazon and Orinoco) (Froelich and Atwood, 1976). At about 150 meters a high salinity (36.5 °/oo to 37.2 °/oo) core called the Subtropical Underwater is found. Between 600 and 800 meters a water core called the Subantarctic Intermediate Water occurs with a minimum in the salinity (about 34.8 °/oo) and below this is found the almost constant Venezuela Basin Water salinity of about 35.00 °/oo. Note that although there is extensive variation in surface salinity there is very little scatter at 1000 meters.

For a more complete discussion of the above mentioned water cores see section I.9, Water Masses.

I.12 Density

This section is included for two reasons:

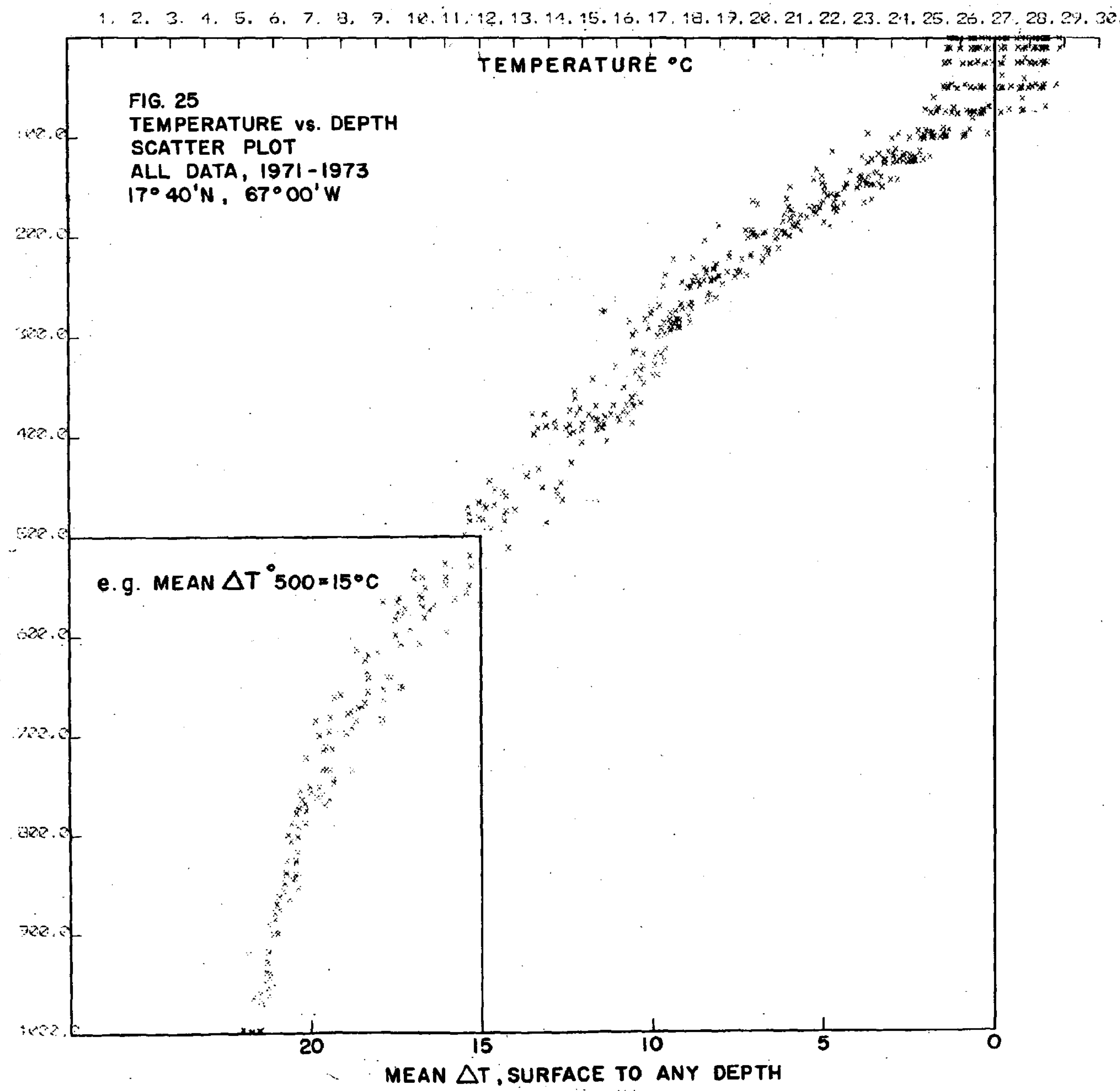
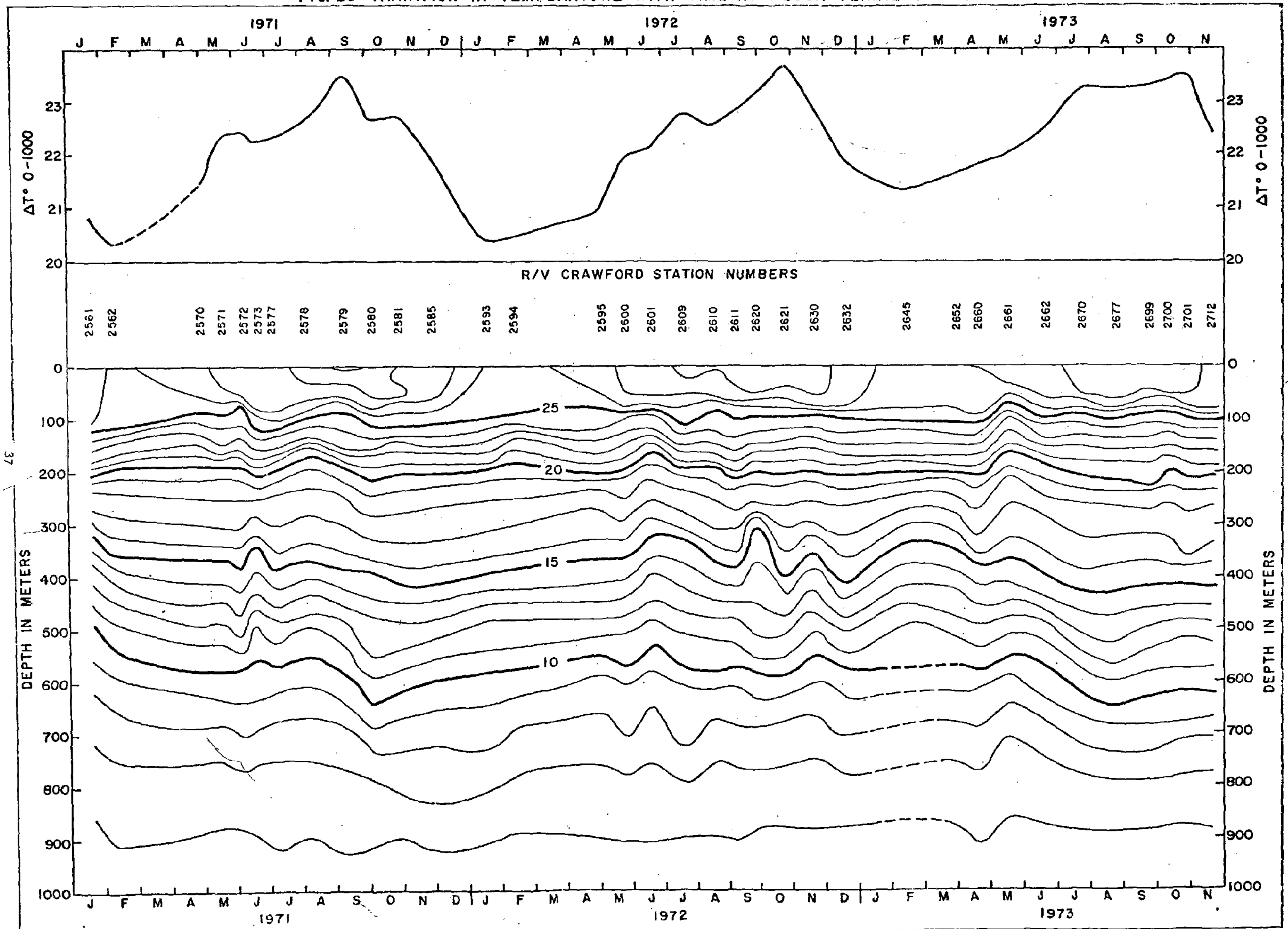


FIG. 25
TEMPERATURE vs. DEPTH
SCATTER PLOT
ALL DATA, 1971-1973
17° 40'N, 67° 00'W

FIG. 26 VARIATION IN TEMPERATURE WITH TIME AT PESCA SERIAL STATION



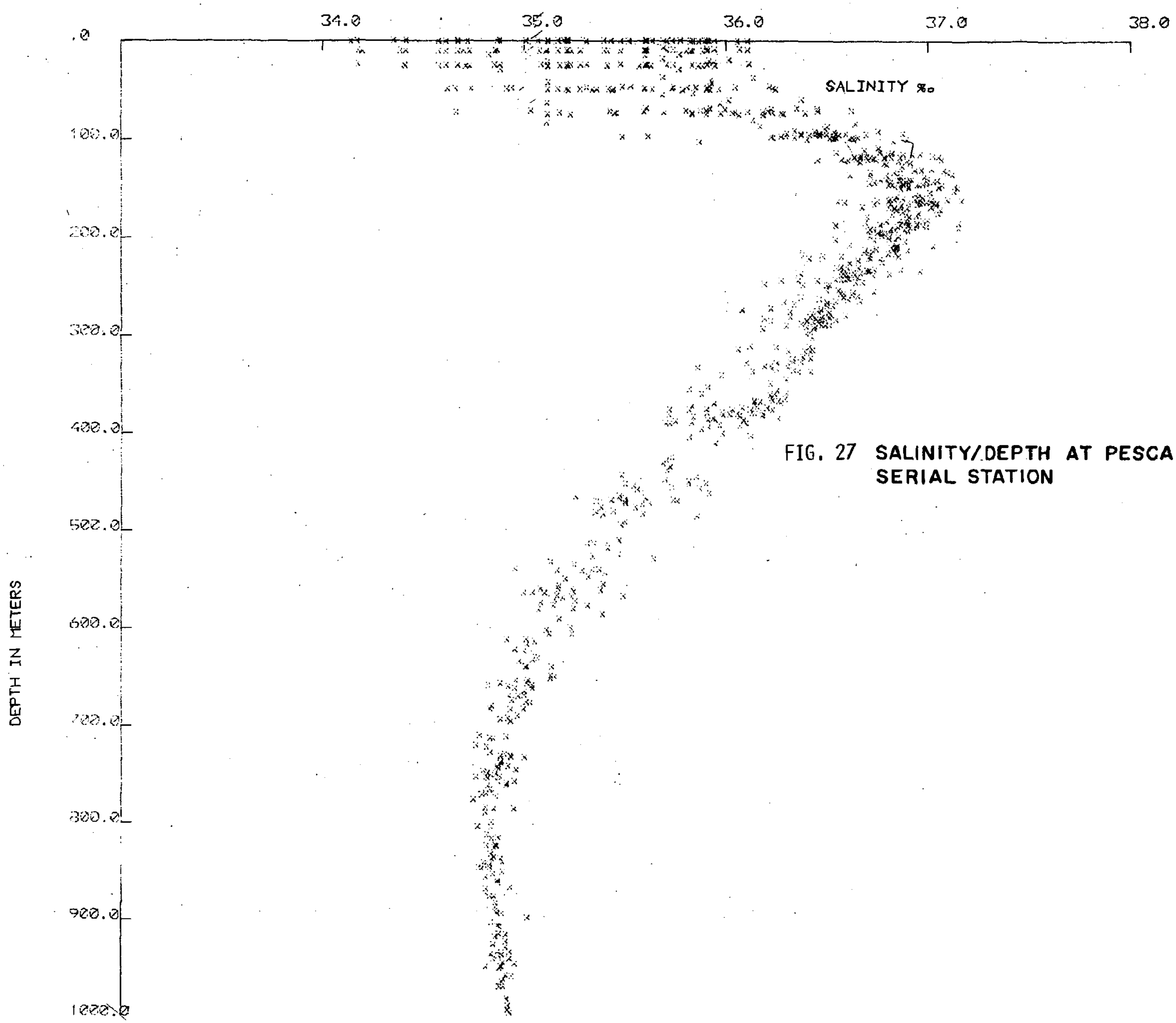


FIG. 27 SALINITY/DEPTH AT PESCA SERIAL STATION

i) To aid in the design of a floating plant
ii) To consider the consequences of the proposed heat-exchange on the water column.

The density of sea water depends on the temperature, salinity and pressure in situ. In the surface waters the pressure effect is negligible, but at 1000 meters accounts for a 0.4% increase in the in situ density. Figure 28 illustrates the variation of density with depth at the PESCA serial station, and an estimate of the variability of density in the surface waters with season. The total density change between the surface and 1000 meters is about .01 g/cc, but this small difference is quite sufficient to keep the water masses separate and distinct. As water is pumped up from depth (say 1000 meters) it is relieved of the pressure and expands slightly. Even though there is a slight adiabatic cooling effect, this expansion effectively reduces the density. Allowing for a 2° C increase in temperature as this water passes through the condensor, the density of the water at the outflow will be about 1.02735 for an initial temperature and salinity of 5.2° C and 34.9 °/°°. Assuming that the surface water is 27.0° C, 35.4 °/°°, with a density of 1.02304, the outflow water will sink, be compressed, and come to rest at a depth of about 800 meters.

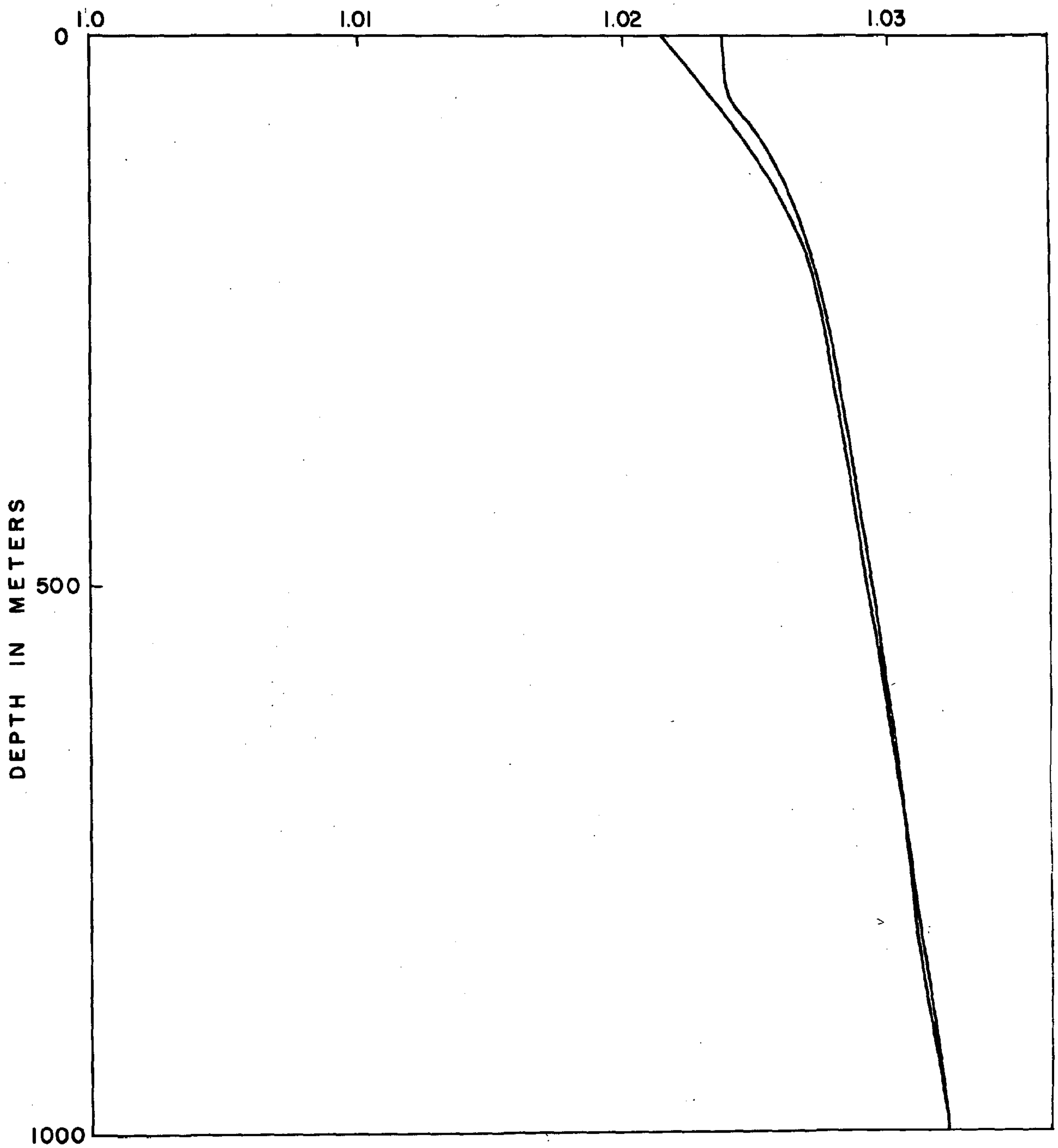
Similarly, the surface water which is cooled by 2° C in the evaporator will have a resultant density of 1.02366 which will float above the thermocline - thereby reducing the effectiveness of the heat source. However, if both intakes are exhausted through the same pipe, being mixed in the process, the density of the resulting mixture will be 1.02587 and the mixture will sink to 200 meters, well removed from either intake and below the euphotic zone. Any further mixing which takes place after the outflow water has reached an equilibrium depth will result in a denser water mass which will sink further by the process known as caballing. The hydrostatic pressure at 1000 meters is about 100 atmospheres and as water is pumped up from this depth it will be replaced laterally from the immense reservoir of VBW. At the surface warm water intake the pressure head is much less, but if the intake is at 20 meters, the replacement supply is more likely to travel horizontally (driven at 30 psi) than vertically. Since the outflow will sink to intermediate depths, it is quite possible that the plant could operate indefinitely even in the absence of currents.

I.13 Currents

A number of atlases of surface currents in the Caribbean have been prepared from ship's drift observations, and they all show the same general pattern, a westerly and northwesterly flow at up to 2 knots, with some flow through the island passages connecting the Caribbean and North Atlantic Gyre. Figures 29 and 30 are reproduced from Wust (1964) but should be considered as giving only a general picture since recent unpublished work indicates that extensive variations to flow depicted occur. Of special note is a relatively permanent easterly flow just north of 15° N indicating the existance of gyres in the northern half of the Caribbean.

FIG. 28

IN SITU DENSITY ENVELOPE — PESCA SERIAL STATION



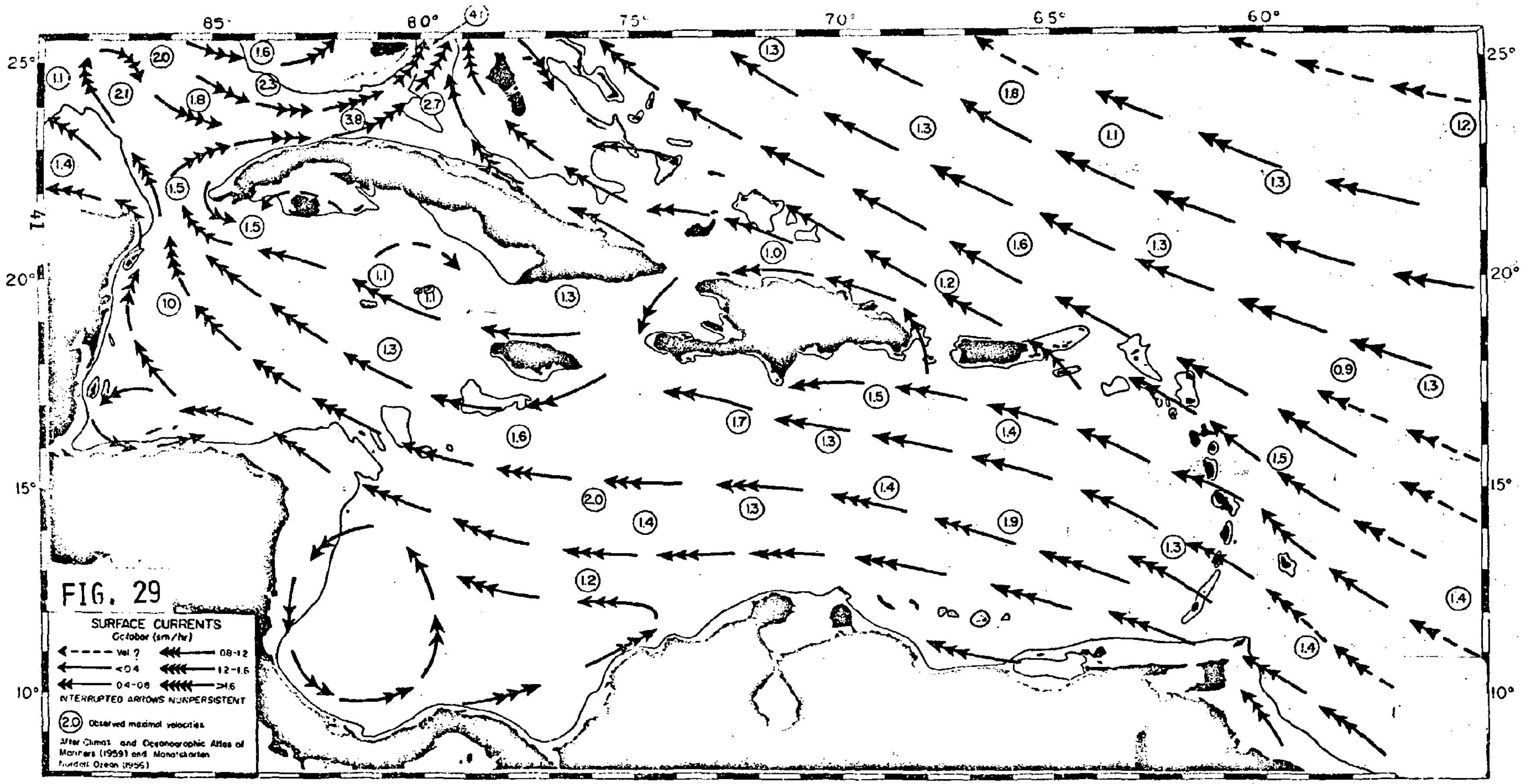
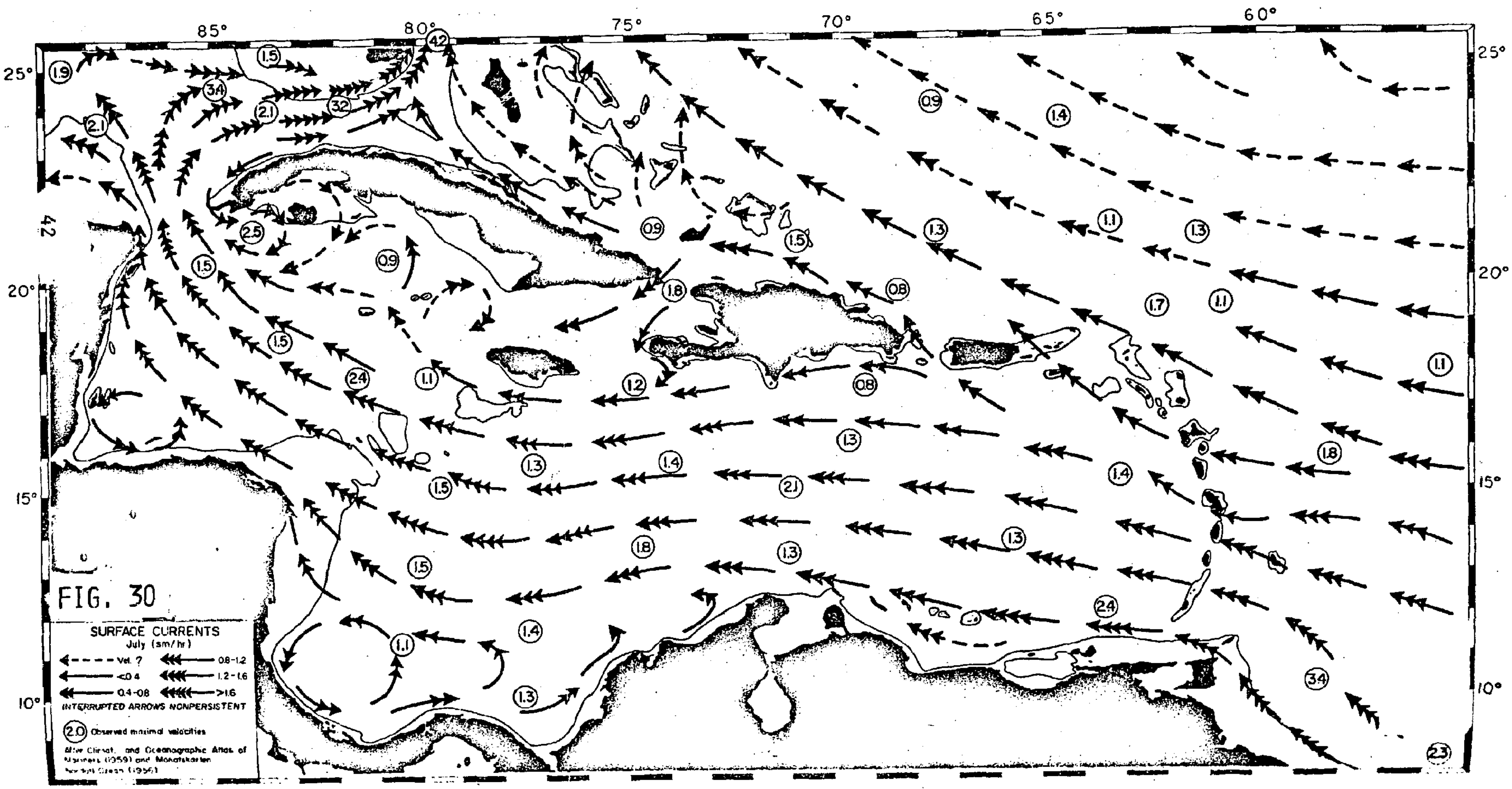

SURFACE CURRENTS
October (sm/hr)
Vel ?
<0.4
0.4-0.8
0.8-1.2
1.2-1.6
>1.6
INTERRUPTED ARROWS NONPERSISTENT
2.0 Observed maximal velocities
After Climat. and Oceanographic Atlas of Mariners (1959) and Monatskarten Nordatl. Ozean (1956)

FIG. 29



85°
80°
75°
70°
65°
60°
25°
20°
15°
10°
SURFACE CURRENTS
July (sm/hr)
Vel. ?
<0.4
0.4-0.8
0.8-1.2
1.2-1.6
>1.6
INTERRUPTED ARROWS NONPERSISTENT
2.0 Observed maximal velocities

FIG. 30

Again, little data can be found specific to the site, or even the coastal waters of the Greater Antilles, but, of the observations made in open water (H.O. Pub. No. 700, Section I), up to 50 % may deviate from the expected westerly or northwesterly flow. Close to a land mass currents usually parallel the coast, with an actual reversal of the open ocean current direction being common. It is expected that the surface flow will be easterly or westerly at the site, the division being about 50 : 50.

Few subsurface current records are available. Figure 31 shows two current profiles near the site, unfortunately with no reference to the number of observations on which they are based. They indicate that large differences in direction with depth can be expected, with low speeds (variable in direction) at the bottom and up to 1 knot at the surface. Geostrophic calculations made using PESCA/CICAR data along 67° W (Figures 32 and 33) indicate that current reversals along the south coast of Puerto Rico may extend to 1000 meters, with surface speeds in excess of 25 cm/sec (½ knot). This easterly flow is no doubt associated with the above mentioned gyre system. An attempt was made to measure deep currents at the Point Tuna/Yabucoa site during the survey described herein (Part II), however, attempts to recover the current meters placed at the site failed.

I.14 Nutrients

As is typical in tropical seas the surface waters of the Caribbean are deficient in nutrient salts. They are removed from the photic zone by plankton which die and sink before all the nutrients can be recycled. A permanent and stable gradient in the thermocline at shallow depths (30 - 100 meters) prevents recirculation of the nutrients to the surface waters once they are removed. As the plankton sink they are oxidized (decay) and return the nutrients to the deeper waters, thus below the euphotic zone nutrients are plentiful. Figures 34, 35 and 36 give the distribution of phosphate, silicate and nitrate with depth at the PESCA serial station. Note that maximums occur in the concentration of nutrients between 600 and 800 meters. The data in Figures 34 and 36 indicate that at this maximum the serial station molar nitrogen and phosphorus ratio is about 15 : 1 which is close to what is considered as the mean world ocean value of 16 : 1 which is the same ratio by which these elements are taken up by phytoplankton (Sverdrup et al., 1942). At the Point Tuna OTEC site we have nitrogen data collected over one complete year which will be discussed under the results of the cruises to that site. (See Part II of this report, section II.5.2).

From the above discussion we can see that the deep water can be considered as an ideally proportioned fertilizer for planktonic growth. An OTEC plant with pumps cooling water from between 600 and 1000 meters will bring some of these nutrients to, or near, the photic zone where they might stimulate plankton growth. Our data on distribution of nutrients with depth allows us to calculate the enrichment of surface waters which might occur once the depth and OTEC plant pumping rate is

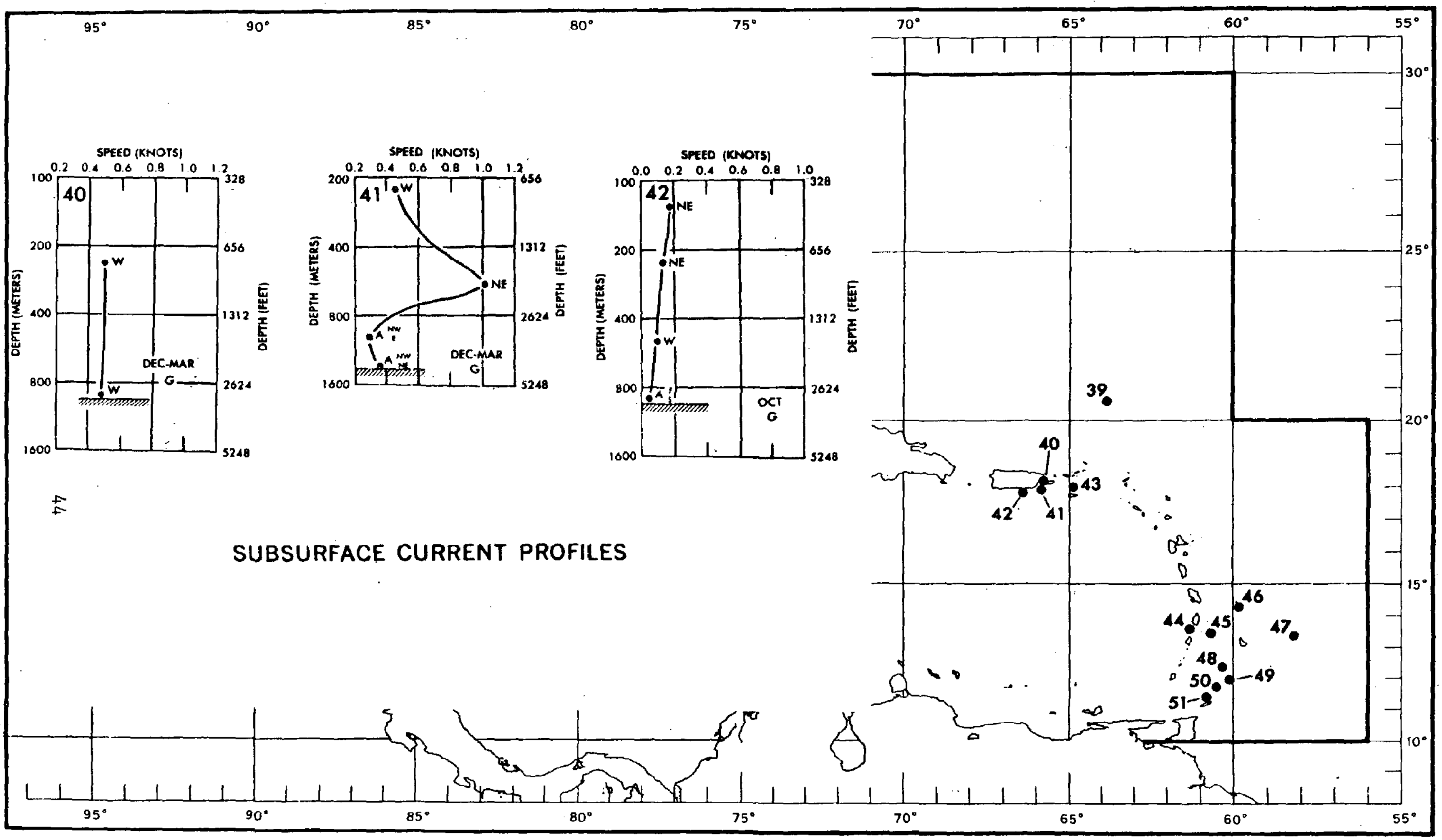


FIGURE 31 — LOCATIONS OF SUBSURFACE CURRENT PROFILES (FROM SP 189 II)

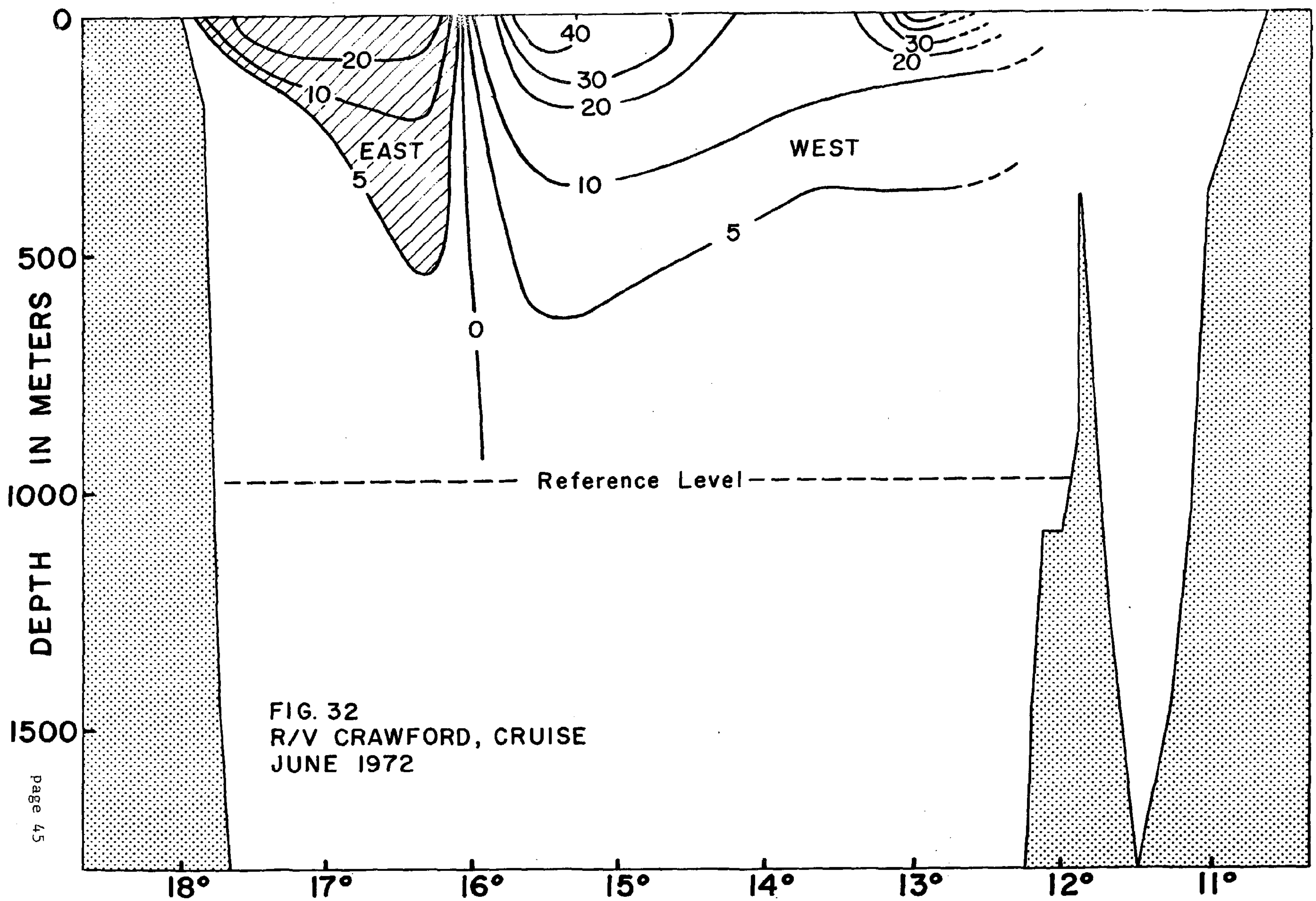


FIG. 32
R/V CRAWFORD, CRUISE
JUNE 1972

GEOSTROPHIC VELOCITIES (cm/sec) FROM PUERTO RICO TO VENEZUELA ALONG 67°W

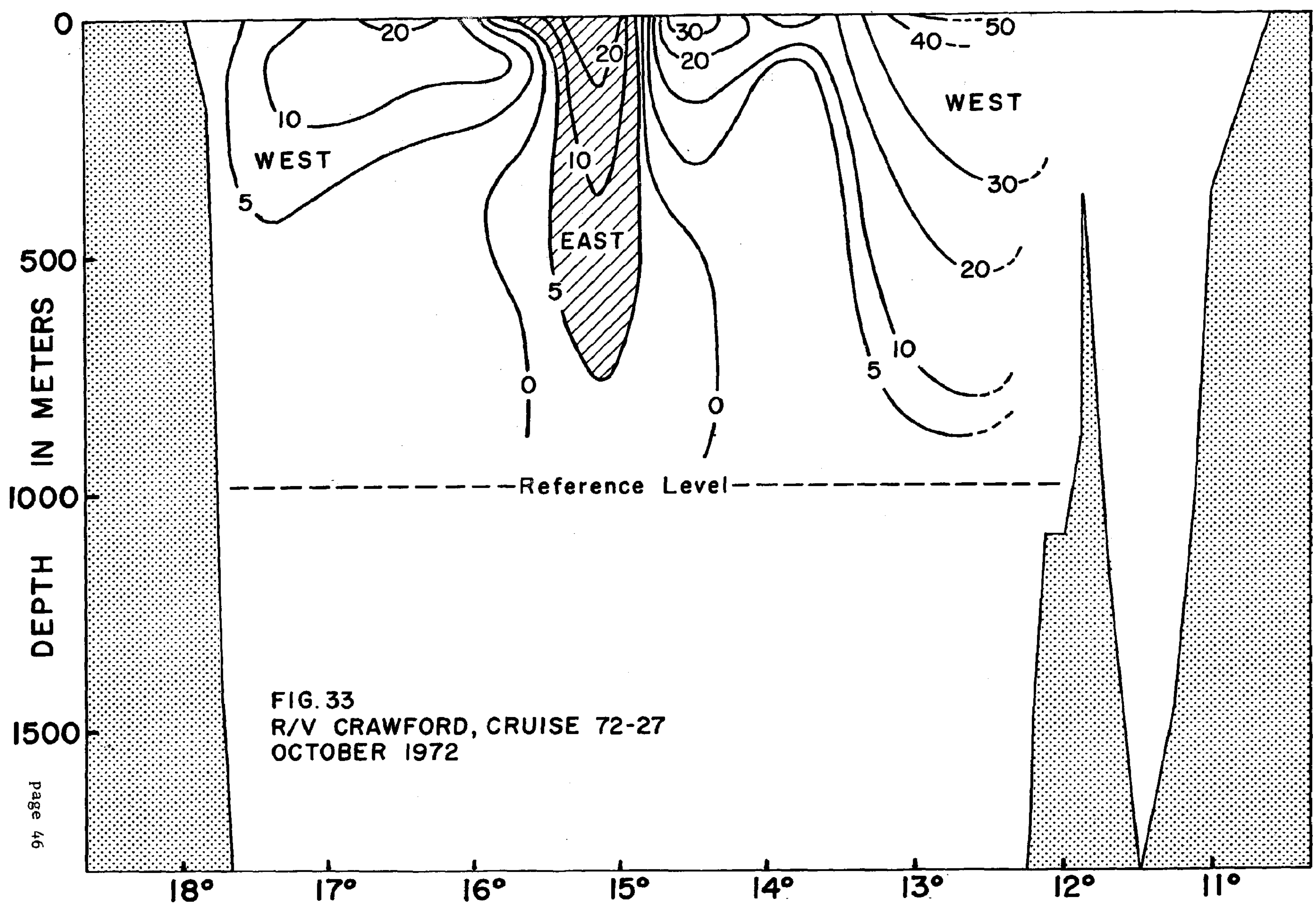


FIG. 33
R/V CRAWFORD, CRUISE 72-27
OCTOBER 1972

GEOSTROPHIC VELOCITIES (cm/sec) FROM PUERTO RICO TO VENEZUELA ALONG 67°W

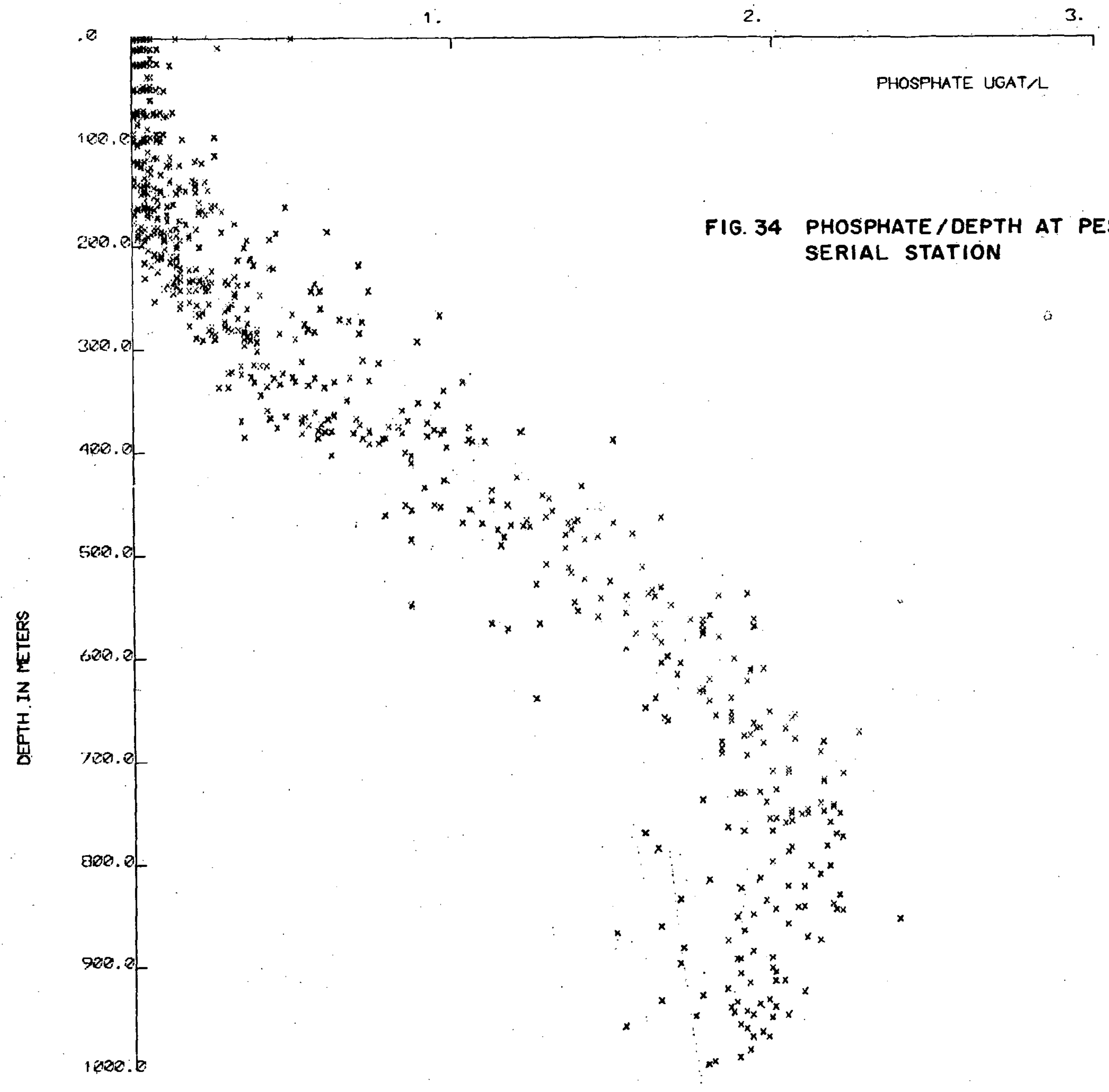


FIG. 34 PHOSPHATE/DEPTH AT PES(
SERIAL STATION

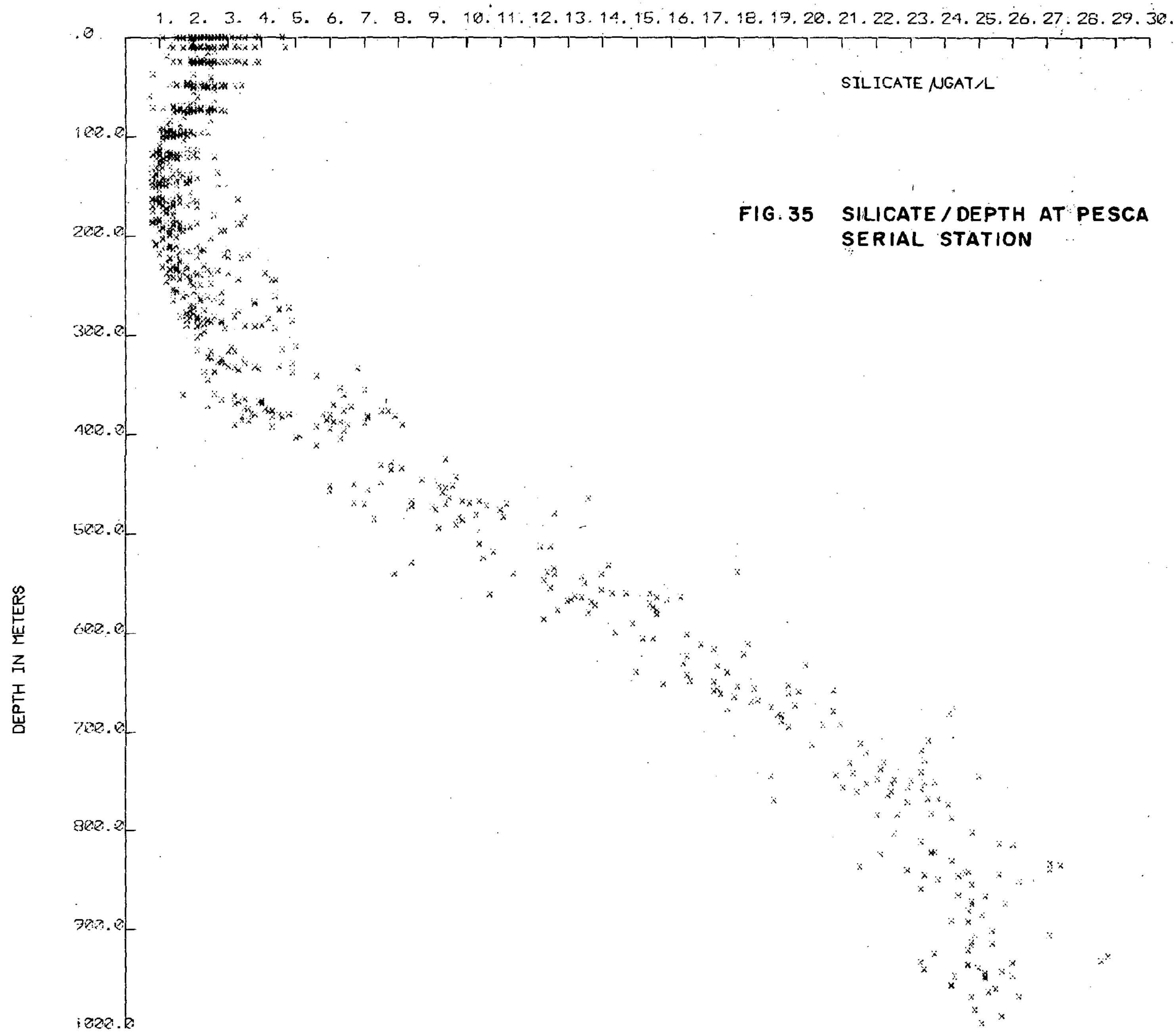


FIG. 35 SILICATE / DEPTH AT PESCA SERIAL STATION

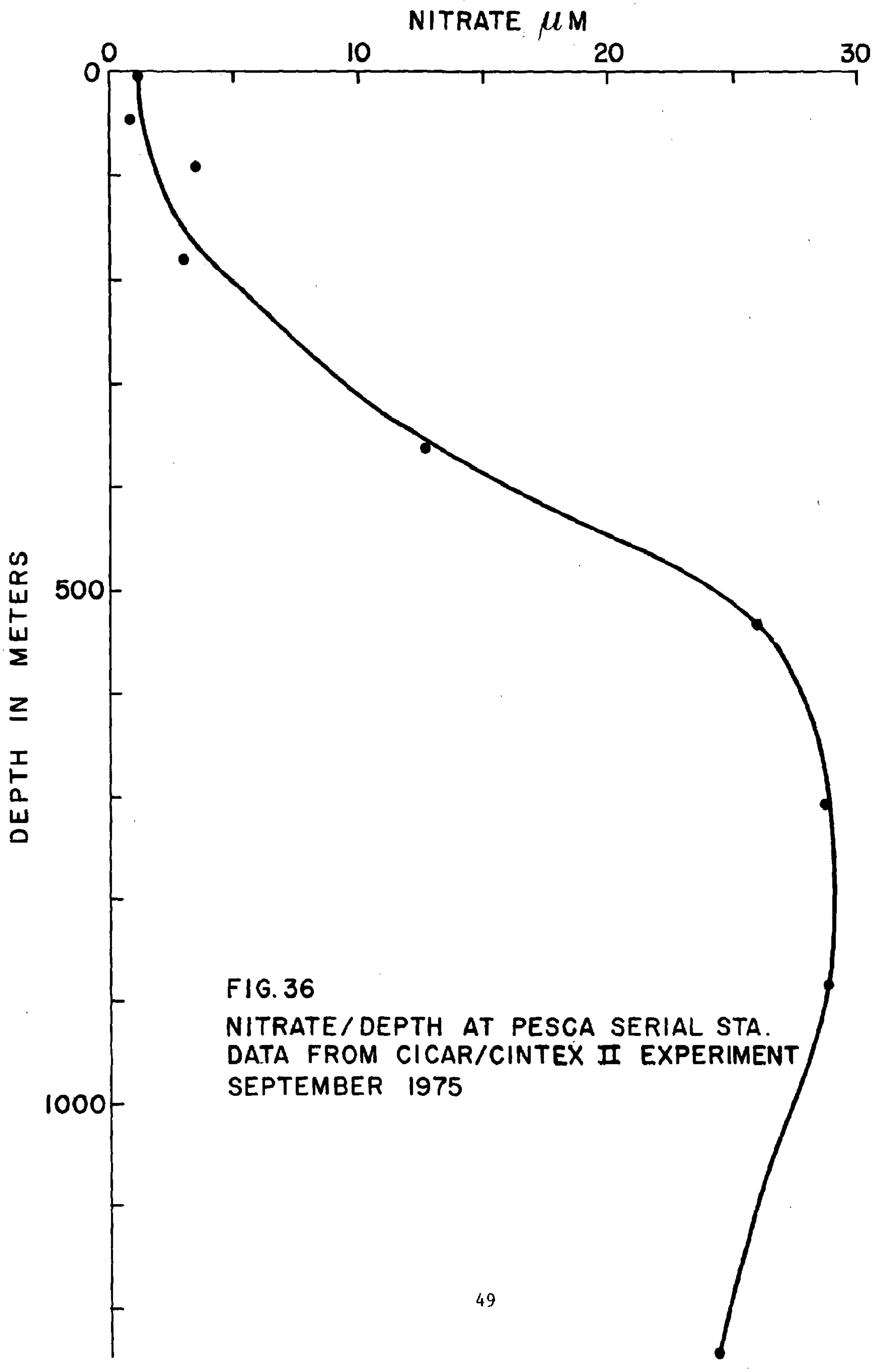


FIG. 36

NITRATE/DEPTH AT PESCA SERIAL STA.
DATA FROM CICAR/CINTEX II EXPERIMENT
SEPTEMBER 1975

known. For each metric ton of water brought to the surface from 1000 meters into ideal photosynthetic conditions (i.e. 100 % conversion of nutrients), some 10 grams of plankton can be grown. This is unfortunately only possible in the surface layer of the ocean, and it is inadvisable to pump cold water into the heat source (see section I.12). Some form of vast water management project could be undertaken, possibly, to take advantage of the "free" nutrients, but it is very doubtful if such a project can be realized when one considers that an OTEC plant pumping 500 m^3/sec of deep water can bring to the surface 43 million m^3/day. This is not a lot compared to natural oceanic flows, it being equivalent to about 0.04% of the rate at which nutrients are carried by the Caribbean Current in the photic zone. <u>However</u>, if this water were pumped into 1 meter deep ponds and held for <u>only one week</u> to allow plankton to bloom, it would require 320 sq. kms. of tank space.

I.15 Oxygen

Figure 37 shows the distribution of oxygen with depth at the PESCA serial station. Near surface values are close to 100% saturation while beneath the surface, saturation is always less than 100%. A slight maximum is observed at about 300 meters which represents water formed in the Sargasso Sea in winter (Kinard, Atwood and Giese, 1974). The oxygen minimum at 600 to 800 meters corresponds to oxygen depleted by oxidation of planktonic detritus and the resultant maximums in nutrient concentration mentioned under the discussion of nutrients (section I.14). The deep water is high in oxygen reflecting the deep circulation of cold, oxygen rich polar waters. There is ample oxygen at all depths to support all forms of marine life.

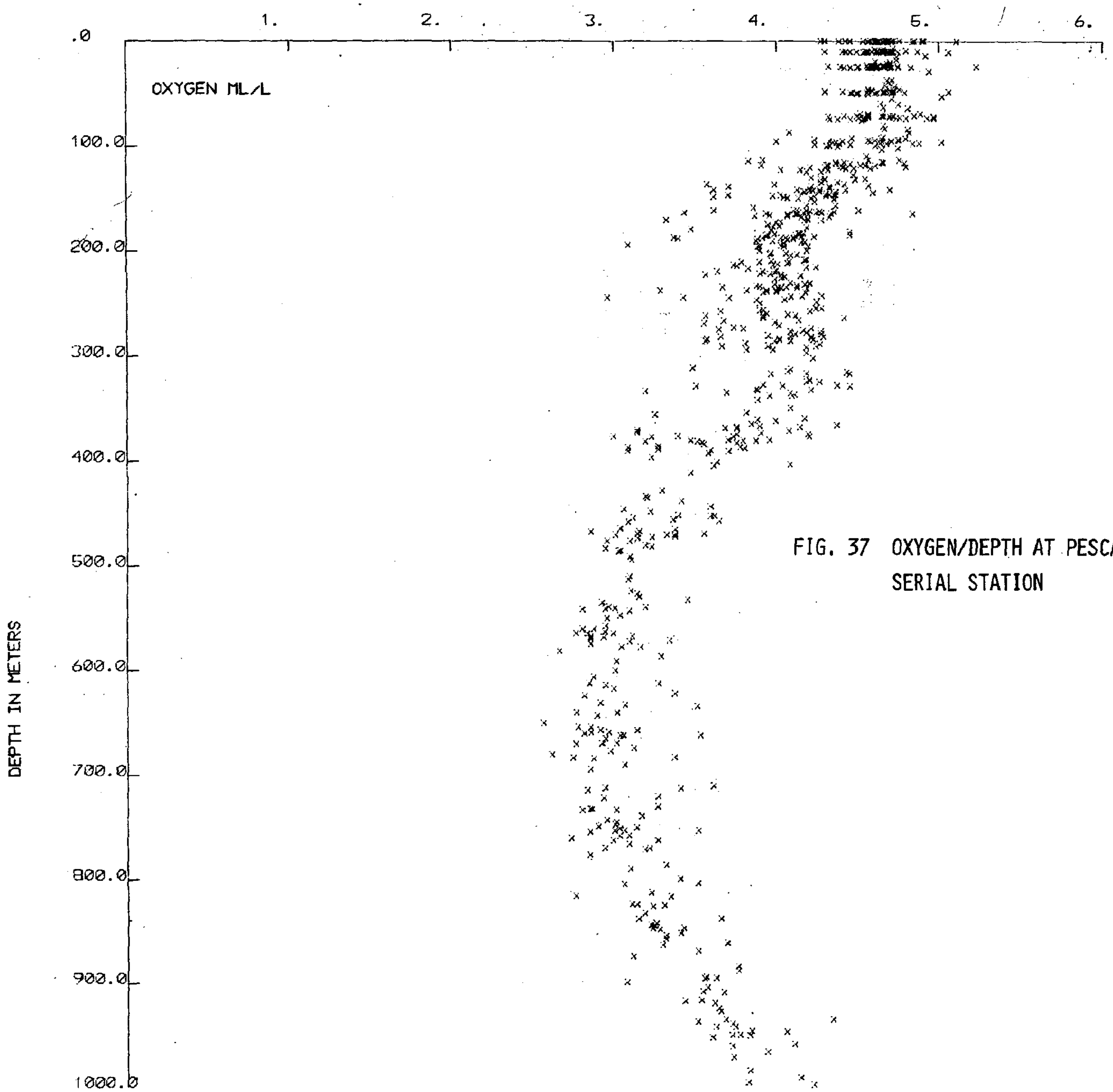


FIG. 37 OXYGEN/DEPTH AT PESCA
SERIAL STATION

PART II: OCEANOGRAPHIC SURVEY OF POINT TUNA/YABUCOA SITE

II.1 Extent of Survey

A hydrographic and bathymetric survey of the Point Tuna/Yabucoa OTEC site has been made by the University of Puerto Rico Marine Science Department and the National Ocean Survey (NOS) of the National Oceanic and Atmospheric Administration (NOAA). The hydrographic data was all collected from the University of Puerto Rico R/V CRAWFORD on four cruises in September 1975, January, March and May 1976. Preliminary bathymetric data was collected from the CRAWFORD in September 1975, however, a complete survey was conducted by the NOAA ship MT. MITCHELL in March and April 1976 and has been compared to historical data collected previously from the NOAA ship WHITING. This bathymetry is discussed in detail in section II.2 of this report.

Table III lists the hydrographic stations occupied by CRAWFORD as well as their dates and positions. Figures 38 through 41 show the positions of these stations at the site area. The prime prototype OTEC location is considered to be just off Point Tuna where stations 2748, 2793, 2825 and 2827 were located. This is due to the proximity of deep cold water close to shore (see Bathymetry in section II.2).

TABLE III

OTEC HYDROGRAPHIC STATIONS OCCUPIED AT THE POINT TUNA/YABUCOA SITE

	Crawford Station Number	Date Mo/Day/Yr	Latitude	Longitude
Cruise # 1	2748	9/ 9/75	17°58.3'N	65°52.6'W
Sept. '75	2749	9/10/75	17°50.5'N	65°43.1'W
	2750	9/10/75	17°55.0'N	65°45.8'W
	2751	9/10/75	17°59.5'N	65°49.8'W
	2752	9/11/75	17°54.0'N	65°52.0'W
	2753	9/11/75	17°48.2'N	65°51.2'W
	2754	9/11/75	17°50.4'N	65°56.8'W
	2755	9/11/75	17°55.2'N	65°58.2'W
Cruise # 2	2793	1/ 8/76	17°57.1'N	65°52.1'W
Jan. '76	2794	1/ 9/76	17°53.8'N	65°52.0'W
	2795	1/ 9/76	17°48.0'N	65°51.4'W
Cruise # 3 March '76	2825	3/11/76	17°57.5'N	65°52.0'W
Cruise # 4	2827	5/11/76	17°58.0'N	65°52.4'W
May '76	2828	5/11/76	17°49.0'N	65°51.0'W

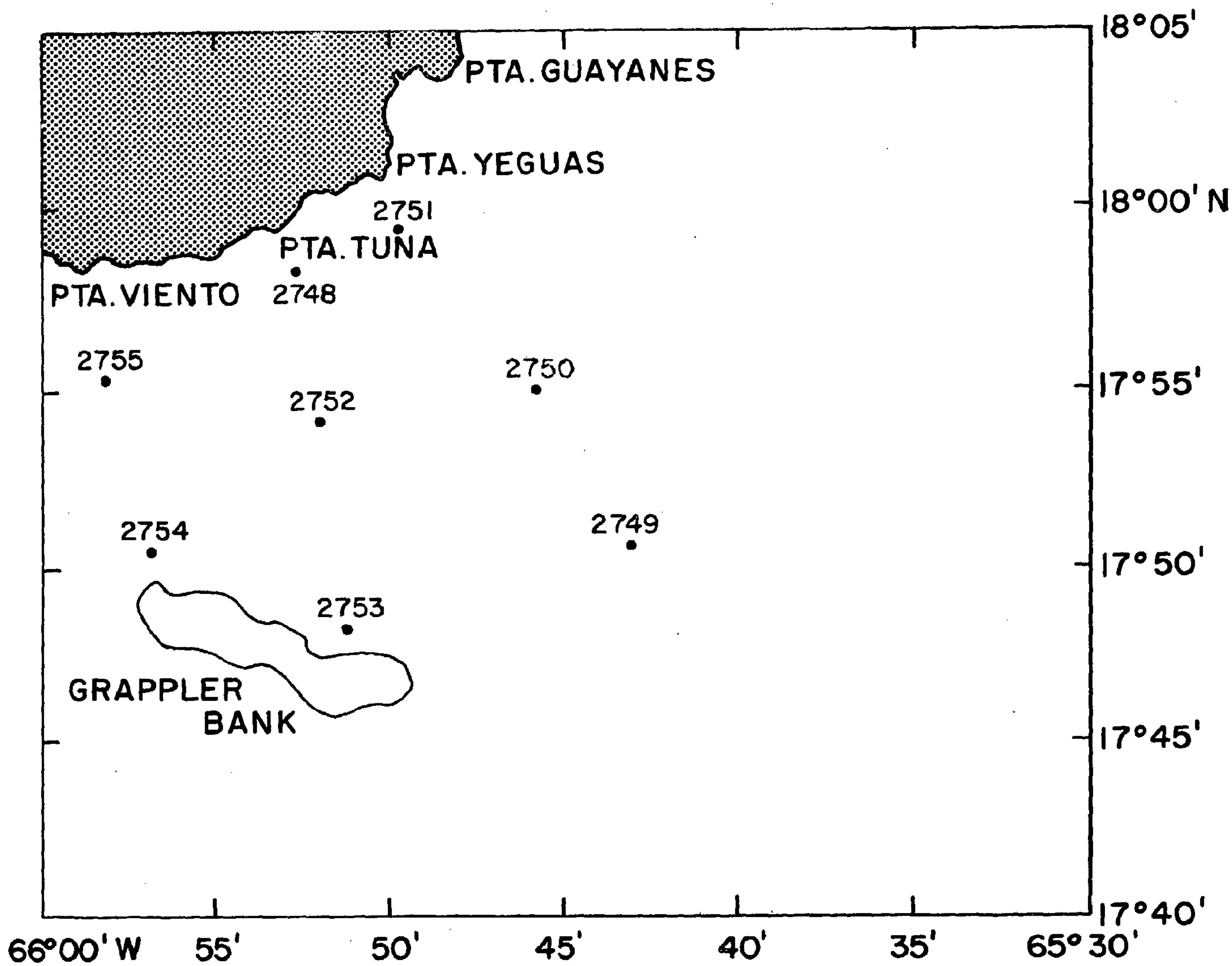


FIG. 38–STATION POSITIONS FIRST OTEC CRUISE – SEPT. 1975

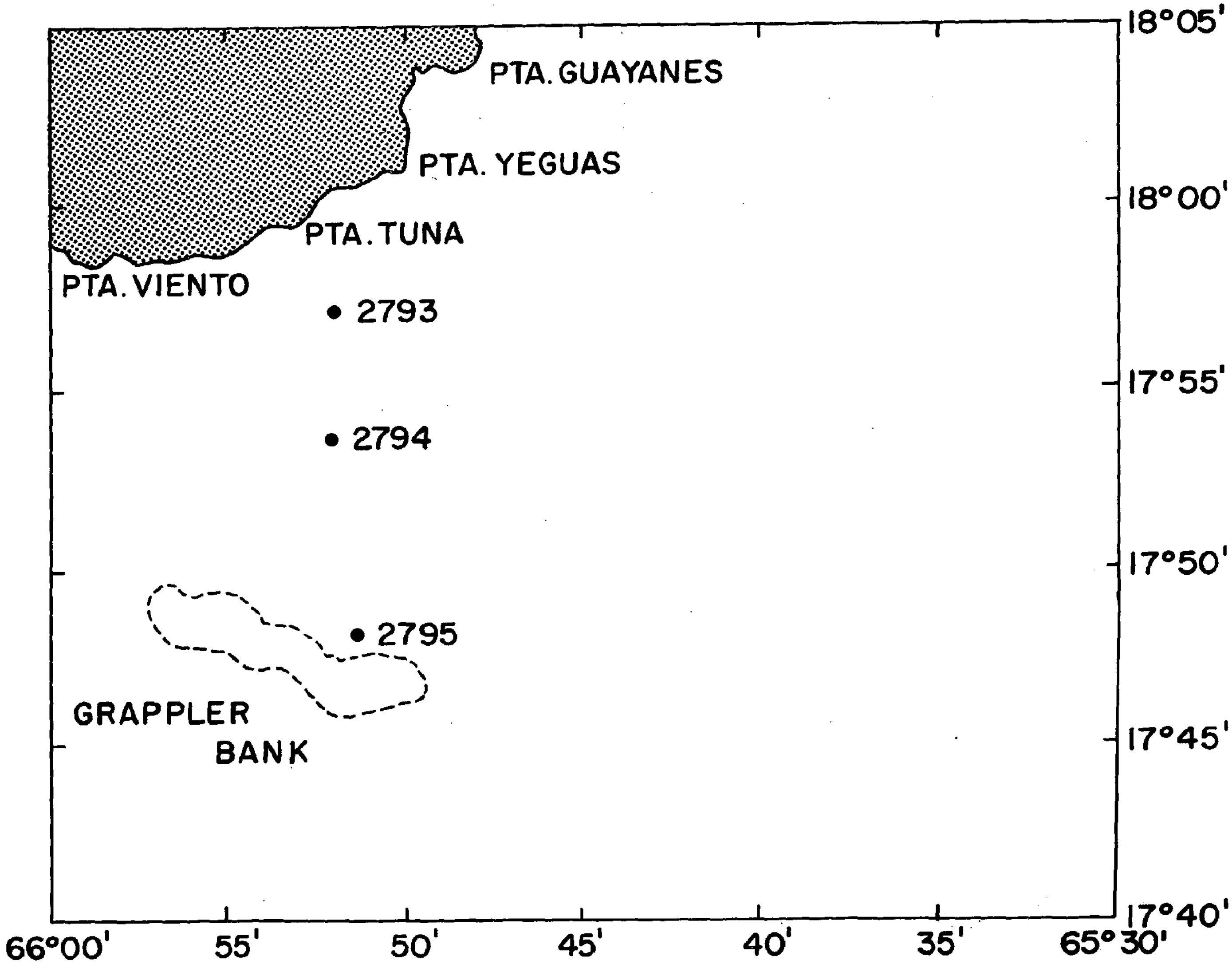


FIG. 39 — STATION POSITIONS SECOND OTEC CRUISE — JAN. 1976

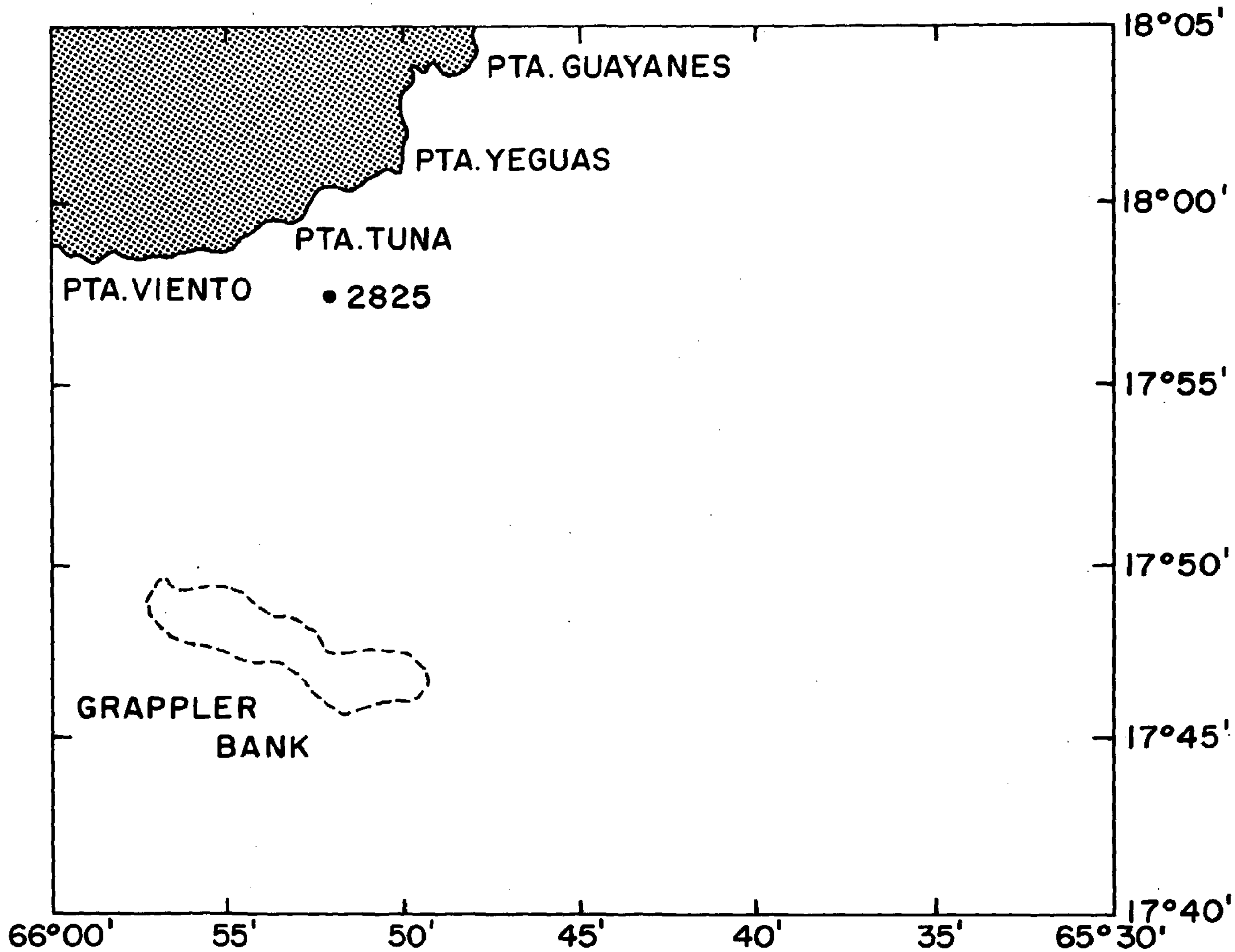


FIG. 40 — STATION POSITION THIRD OTEC CRUISE — MARCH 1976

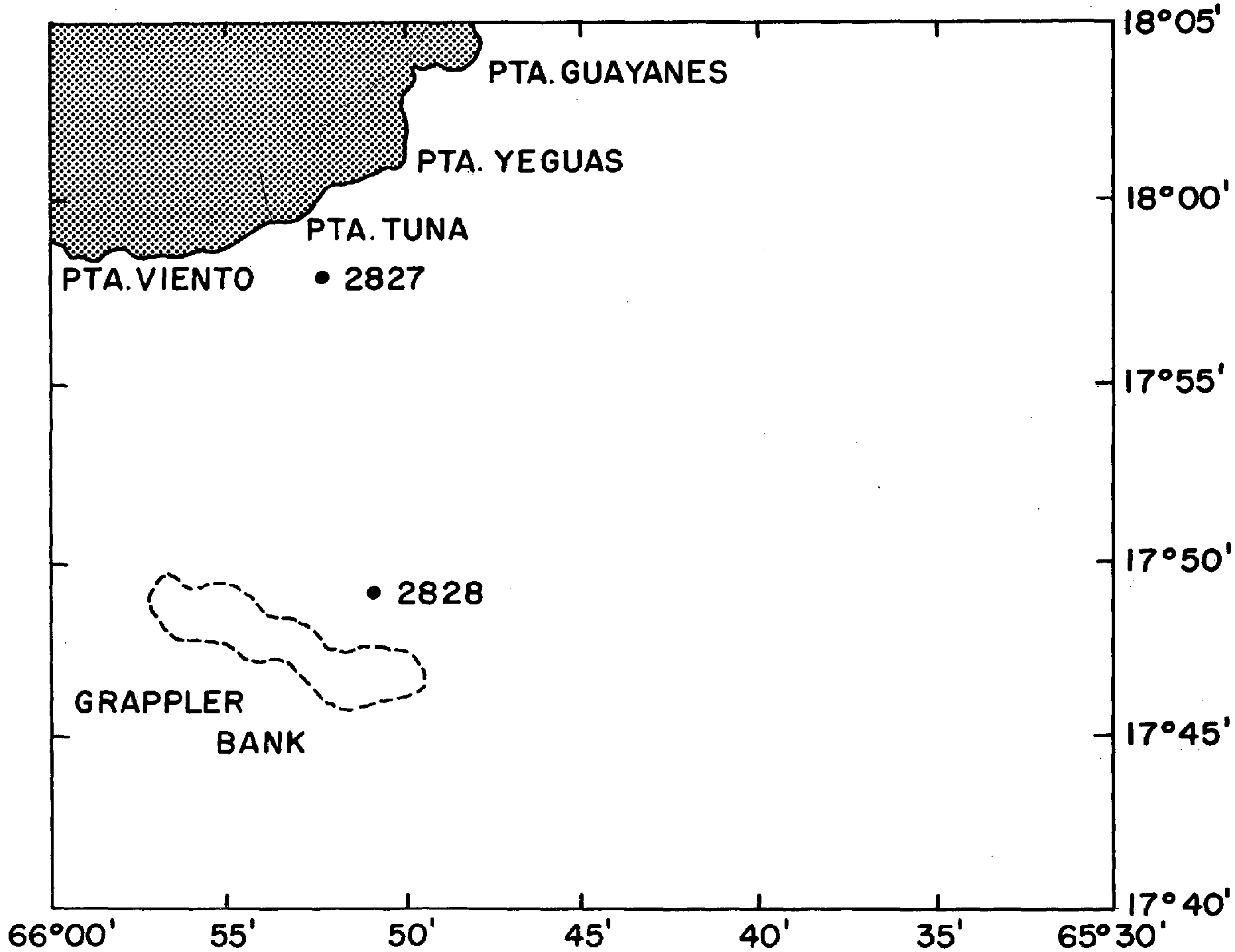


FIG. 41 — STATION POSITIONS FOURTH OTEC CRUISE — MAY 1976

II.2 Bathymetry

The bathymetry of the southeast coast of Puerto Rico near the Point Tuna/Yabucoa site is shown in Figure 42. Contours are meters cor rected for the speed of sound in sea water according to Matthews (1939) Frasetto and Northrup (1957) indicate that depths east of here, near th middle of the Virgin Islands Basin exceed 4,400 m and Stalcup and Metcalf (1973) show that the Anegada Sill, at a depth of 1960 m, is the controlling sill for this basin. Water in the Atlantic Ocean at this depth and near the Anegada Sill has a potential temperature of 3.6° C and originates in the surface layers of the Labrador Sea. Wright (1972 estimates an average production of 3.5 x 10^6 m^3 sec $^{-1}$ of Labrador Sea water. The deep water off the southeast coast of Puerto Rico is in direct communication with the Atlantic at depths shallower than 1960 m thus ensuring a virtually limitless supply of deep cold water to this area.

Bathymetric profiles offshore from Point Tuna (A) and near Point Yeguas (B) are shown in Figure 43. Water deeper than 1,000 m (at a potential temperature of 5.2° C) is found 3.3 km from Point Tuna and 2.6 km from Point Yeguas.

The Coast and Geodetic Survey chart #920 indicates that the bottor in this area is hard and is composed of yellow clay, yellow sand, blue mud and coral. A gravity core taken off Point Tuna during this study consisted of coral sand with mud.

II.3 Temperature

II.3.1 Seasonal Variations

Figures 44 through 47 are plots of temperature versus depth using temperature and depth measurements obtained from protected and unprotected thermometers during each of the four cruises to the Point Tuna/Yabucoa OTEC site. Figure 48 is a composite plot of the same thing for all four cruises. The plots show that the surface temperature varie from a maximum of 29.2° C in September 1975 to a minimum of 24.5° C in March 1976. By May 1976 the surface temperature had risen back up to 26.7° C. In contrast the temperature at 800 meters varied only from 6.5° C to 7.0° C and at 1000 meters was a constant 5.1 ± 0.1° C. The Δ T between the surface mixed layer and 800 and 100 meters varied as shown in Table IV.

TABLE IV

Δ T BETWEEN SURFACE AND 800 AND 1000 METERS
FOR POINT TUNA/YABUCOA OTEC SITE

Depth	Δ T ° C From Sfc.			
Meters	Sept. '75	Jan. '76	March '76	May '76
800	21.8	19.0	18.3	20.2
1000	23.3	20.2	19.4	21.3

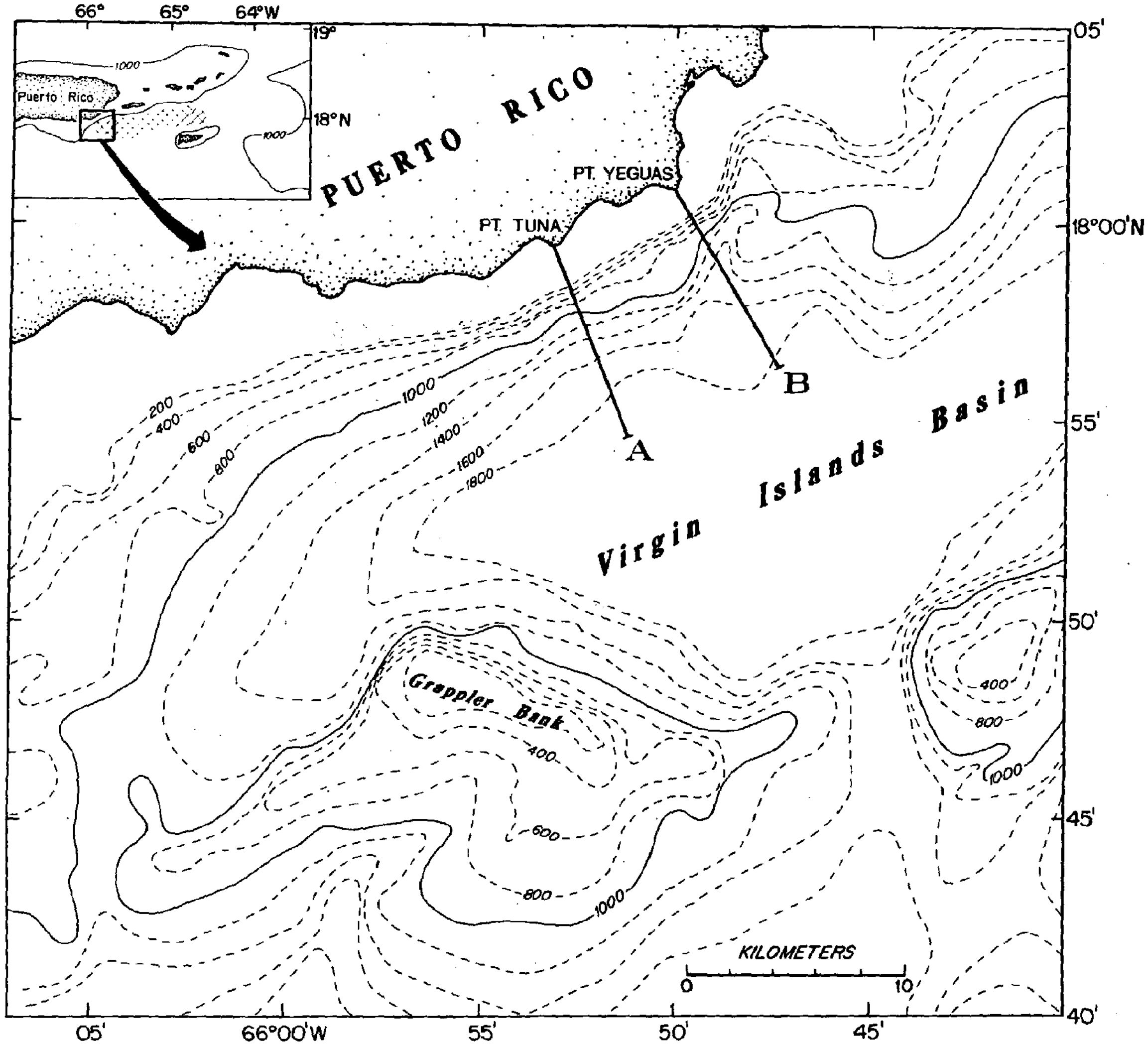


FIG. 42 Chart of the bathymetry in the western portion of the Virgin Islands Basin (hatched area in inset) southeast of Puerto Rico. Depth contours are in meters corrected for the speed of sound in sea water (Matthews, 1939). Data courtesy of NOAA, National Ocean Survey and from a bathymetric survey conducted during the present study.

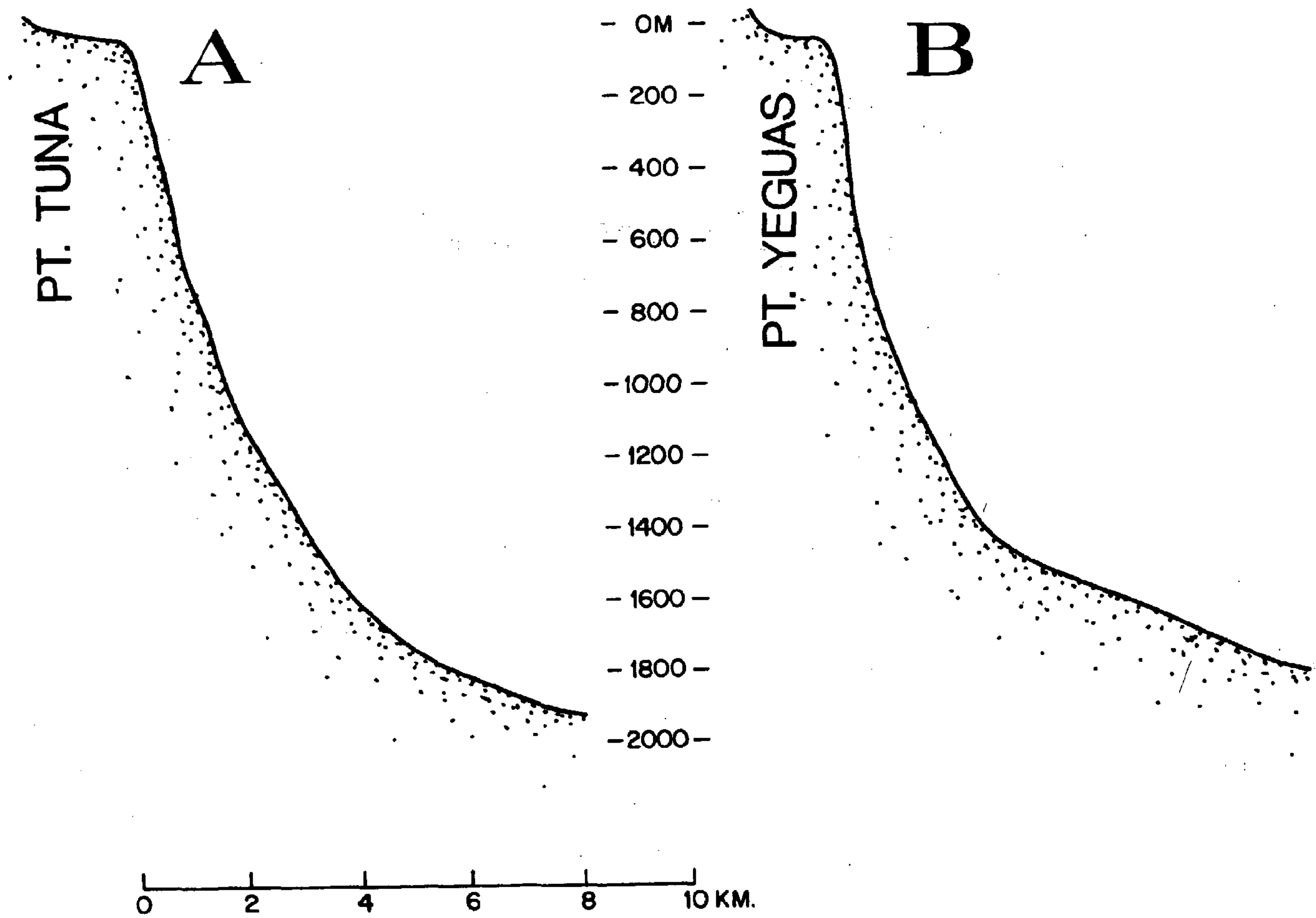


FIG. 43 Bathymetric profiles offshore from Point Tuna (A) and Point Yeguas (B) along lines shown in Figure 1. Depths are meters corrected for the speed of sound in sea water and distance is kilometers.

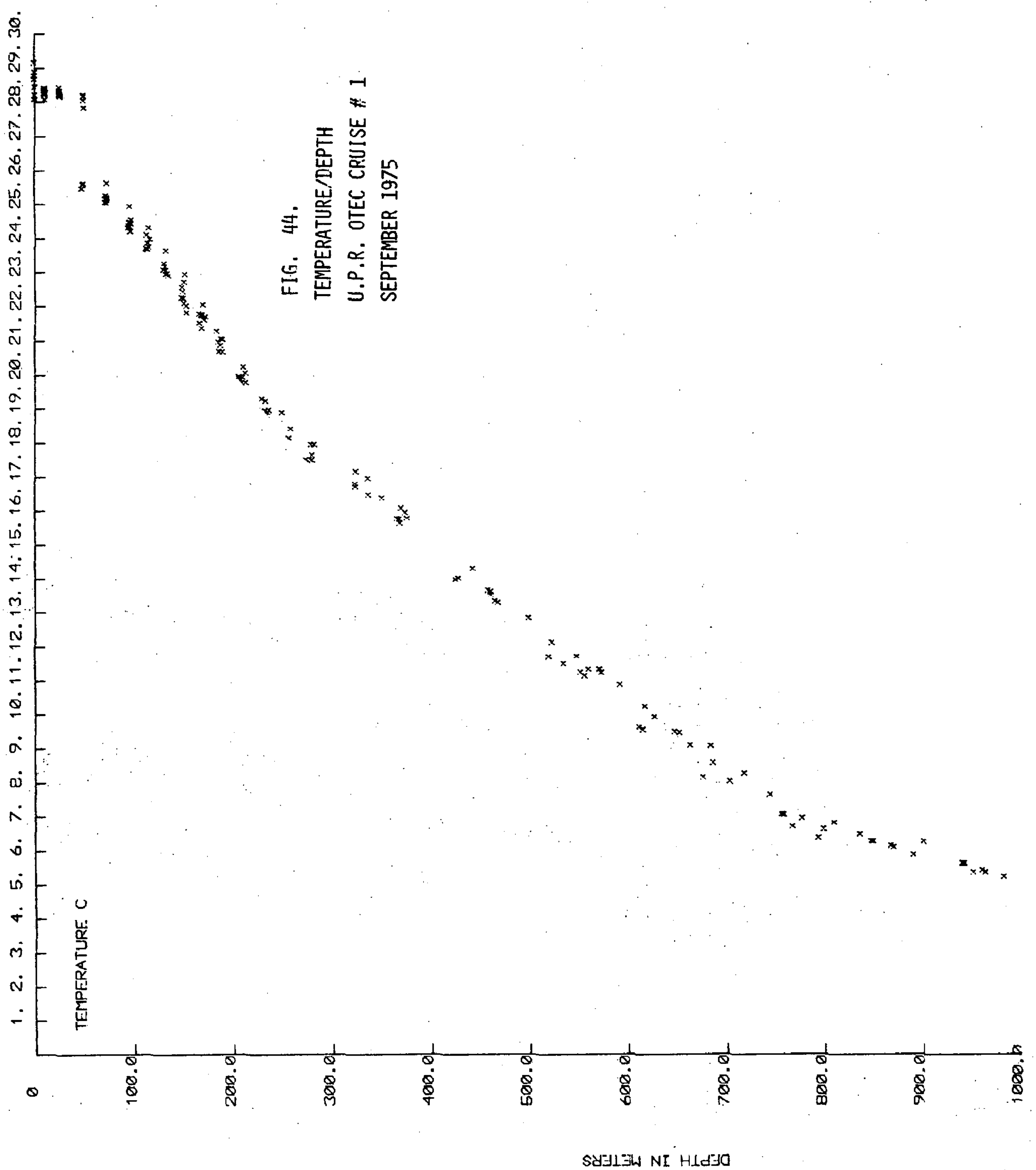


FIG. 44.
TEMPERATURE/DEPTH
U.P.R. OTEC CRUISE # 1
SEPTEMBER 1975

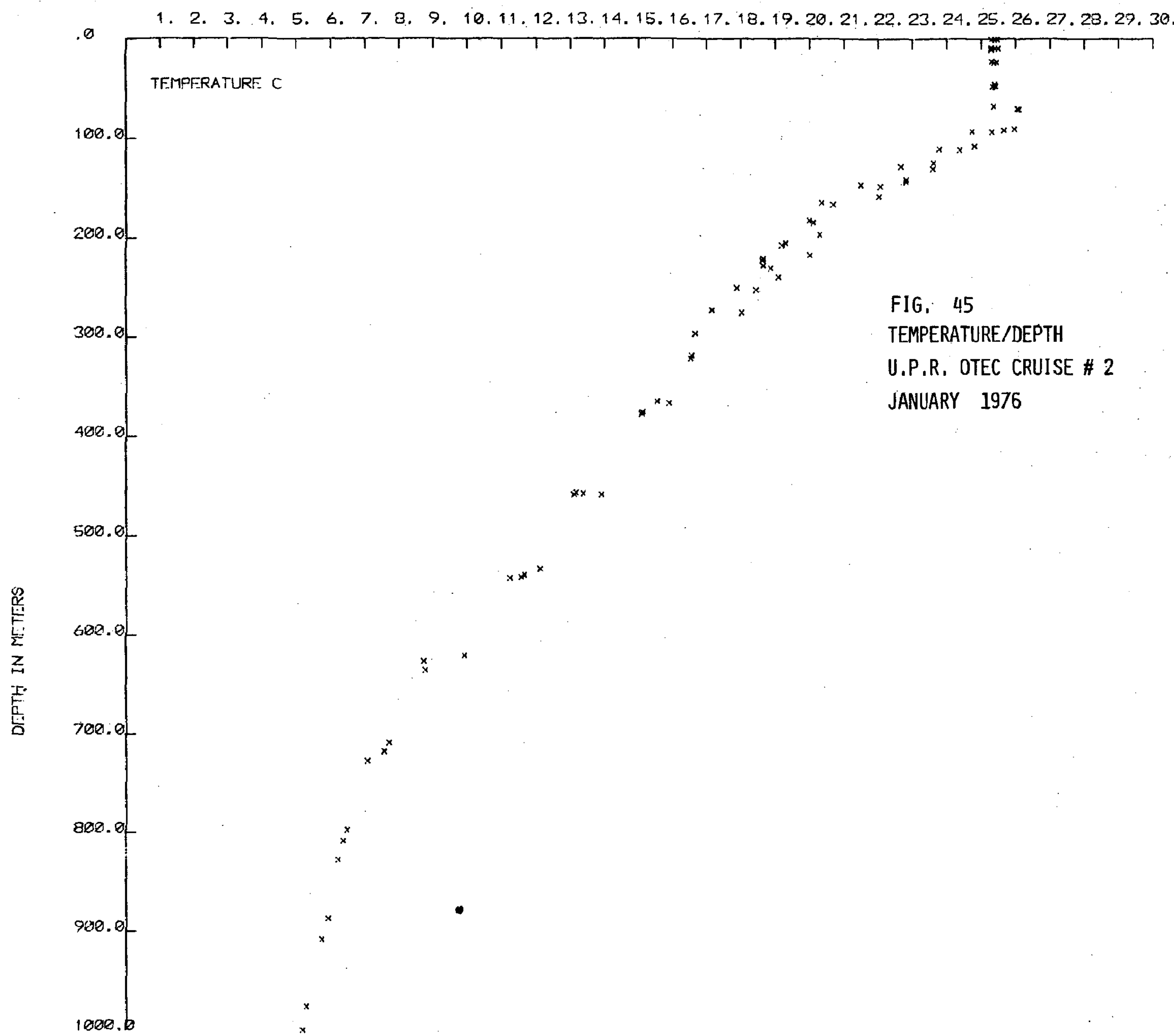


FIG. 45
TEMPERATURE/DEPTH
U.P.R. OTEC CRUISE # 2
JANUARY 1976

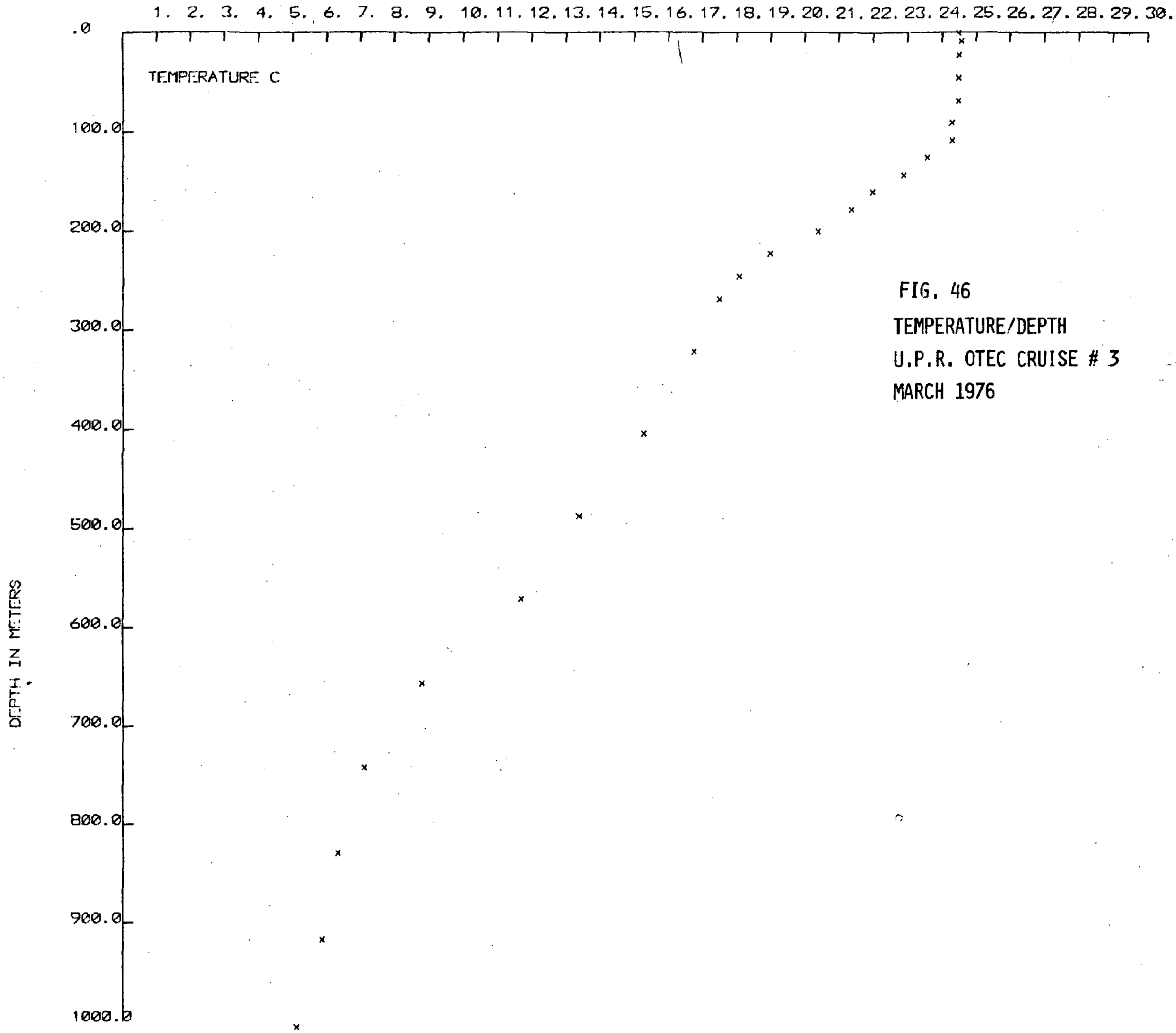


FIG. 46
TEMPERATURE/DEPTH
U.P.R. OTEC CRUISE # 3
MARCH 1976

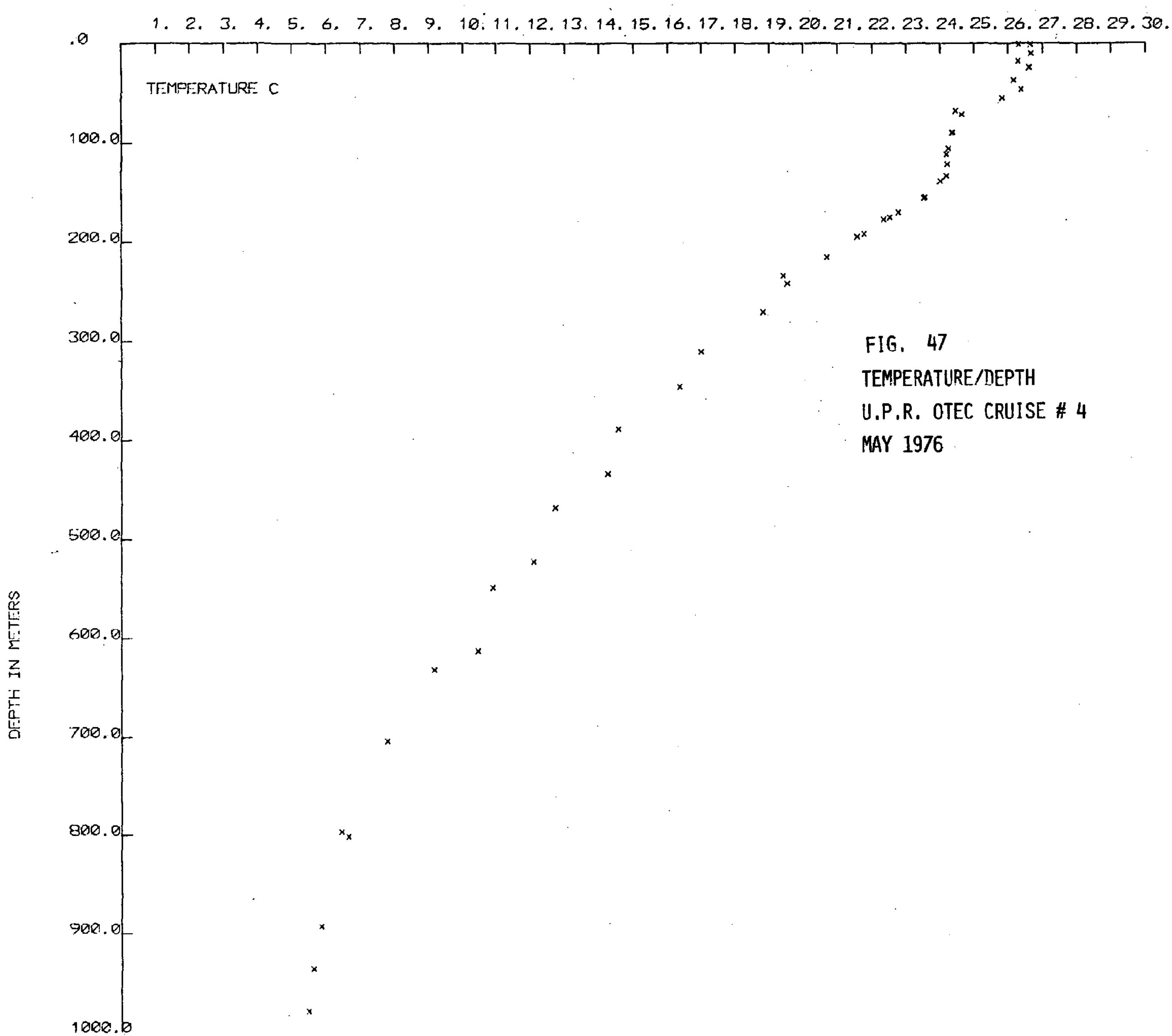


FIG. 47
TEMPERATURE/DEPTH
U.P.R. OTEC CRUISE # 4
MAY 1976

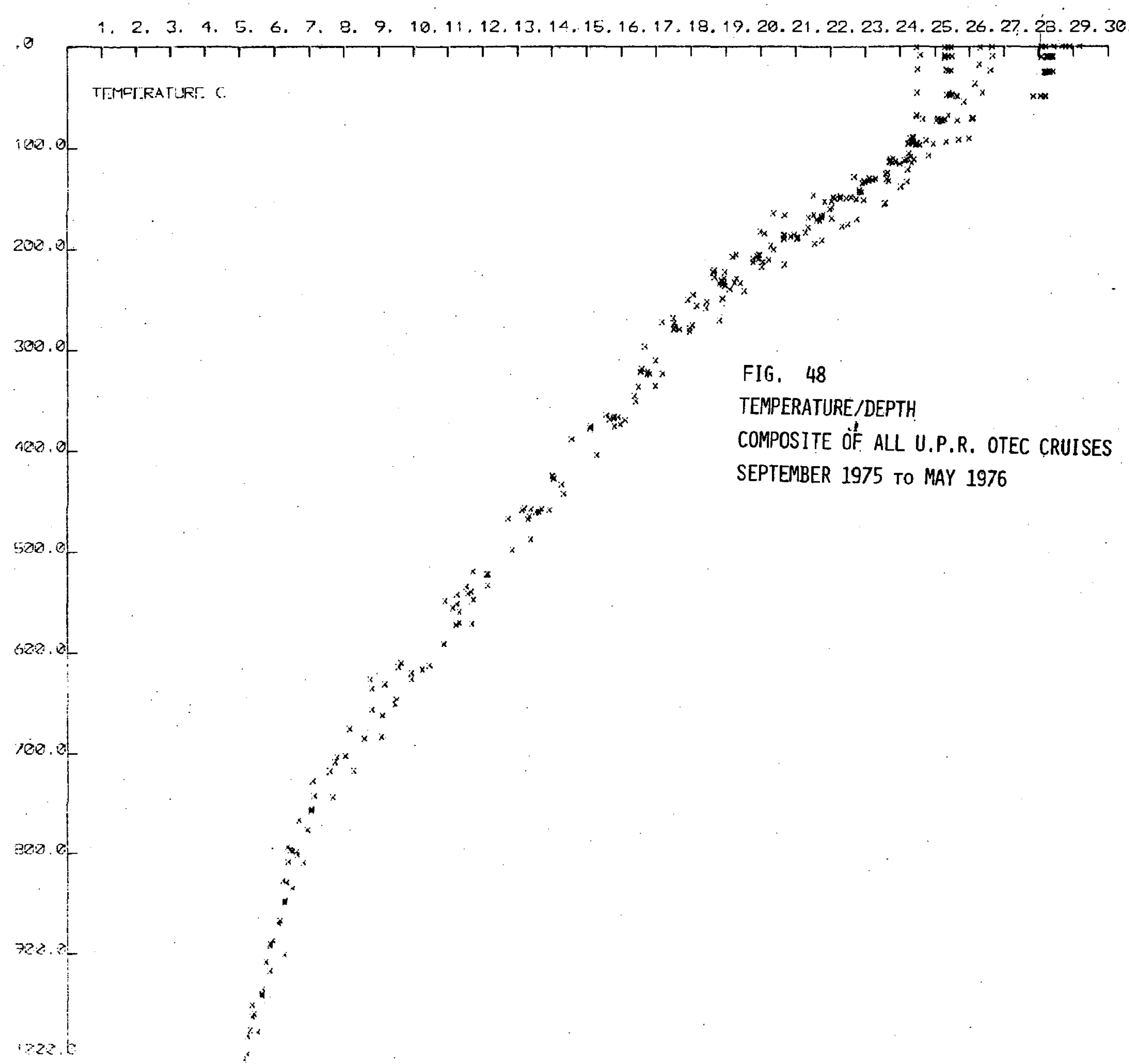


FIG. 48
TEMPERATURE/DEPTH
COMPOSITE OF ALL U.P.R. OTEC CRUISES
SEPTEMBER 1975 TO MAY 1976

TABLE V

SUMMARY OF HYDROGRAPHIC STATIONS REPRESENTED

IN TEMP/DEPTH PLOT FOR HAWAII AREA

Ship*	Country	Station Number	Date D-M-Y	Latitude	Longitude
HH	Japan	OC7	11-IX-69	20°59.0'N	154°59.0'W
YQ	USA	HAH	31- V-66	22°53.8'N	158°54.7'W
YQ	USA	HAH	1-VI-66	24°30.6'N	161°30.0'W
CQ	USA	004	2-VI-71	21°29.0'N	157°03.0'W
PI	USA	0069	12- X-61	23°30.0'N	160°00.0'W
PI	USA	P021	9-IX-61	23°28.0'N	162°56.0'W
PI	USA	P028	10-IX-61	23°56.0'N	167°20.0'W
PI	USA	105	6- V-63	25°01.0'N	165°01.0'W
VI	USSR	4317	2-II-59	20°00.0'N	158°09.0'W

* Ship's names represented by NODC code

The depth of the mixed layer varied from minimums of about 50 meters (in both September 1975 and May 1976) to greater than 100 meters (in March 1976). However, at no time was the water above 75 meters colder than 24° C and in May 1976, 24° C water was available to a depth of > 150 meters. It is interesting to note the discontinuities in the temperature/depth profile within the mixed layer or at the base of it. These are present in the plots for September 1975 and for January and May 1976. In September 1975 and May 1976 the discontinuity indicates that the mixed surface water advecting into the area is gaining heat from radiant energy faster than heat is diffusing downward below 50 meters. By contrast, in January 1976 the surface mixed layer was losing heat to the atmosphere faster than it diffused upward. Apparently in March 1976 an equilibrium situation existed.

Figure 49 shows a vertical section of temperature versus depth for stations 2748, 2752 and 2753, taken in September 1975 (see Figure 38 for station locations). Except for minor transient variations it seems obvious that at any one time the temperature profile does not vary much from place to place within the site area. The isotherms in Figure 49 are, in fact, virtually horizontal.

Below 1000 meters the site area has slightly lower temperatures than the Venezuela Basin since it is actually located in the Virgin Island and/or Whiting Basins where a deeper sill (Anegada Sill) allows colder North Atlantic Deep Water to flow into the area than into the Venezuela Basin.

II.3.2 Comparison to Hawaii Area Temperatures

Figure 50 is a composite plot of temperature versus depth for the hydrographic stations listed in Table V. These stations are all in the vicinity of Hawaii and represent data taken in the months of February, May, June, September and October. Since Hawaii has received consideration as a potential OTEC site it seems pertinent to compare the temperature regime to the Puerto Rico site. This can be done by comparing Figures 25 and 48 to 50. Some general results of this comparison are listed in Table VI.

TABLE VI

Parameter	Puerto Rico Site	Hawaii Area
Surface Temperature	24.5 - 29.2° C	23.2 - 27.0° C
Δ T to 800 meters	18.3 - 21.8° C	19.0 - 22.2° C
Δ T to 1000 meters	19.4 - 23.3° C	19.7 - 22.9° C
Depth of mixed layer	50 - >100 meters	50 - 100 meters

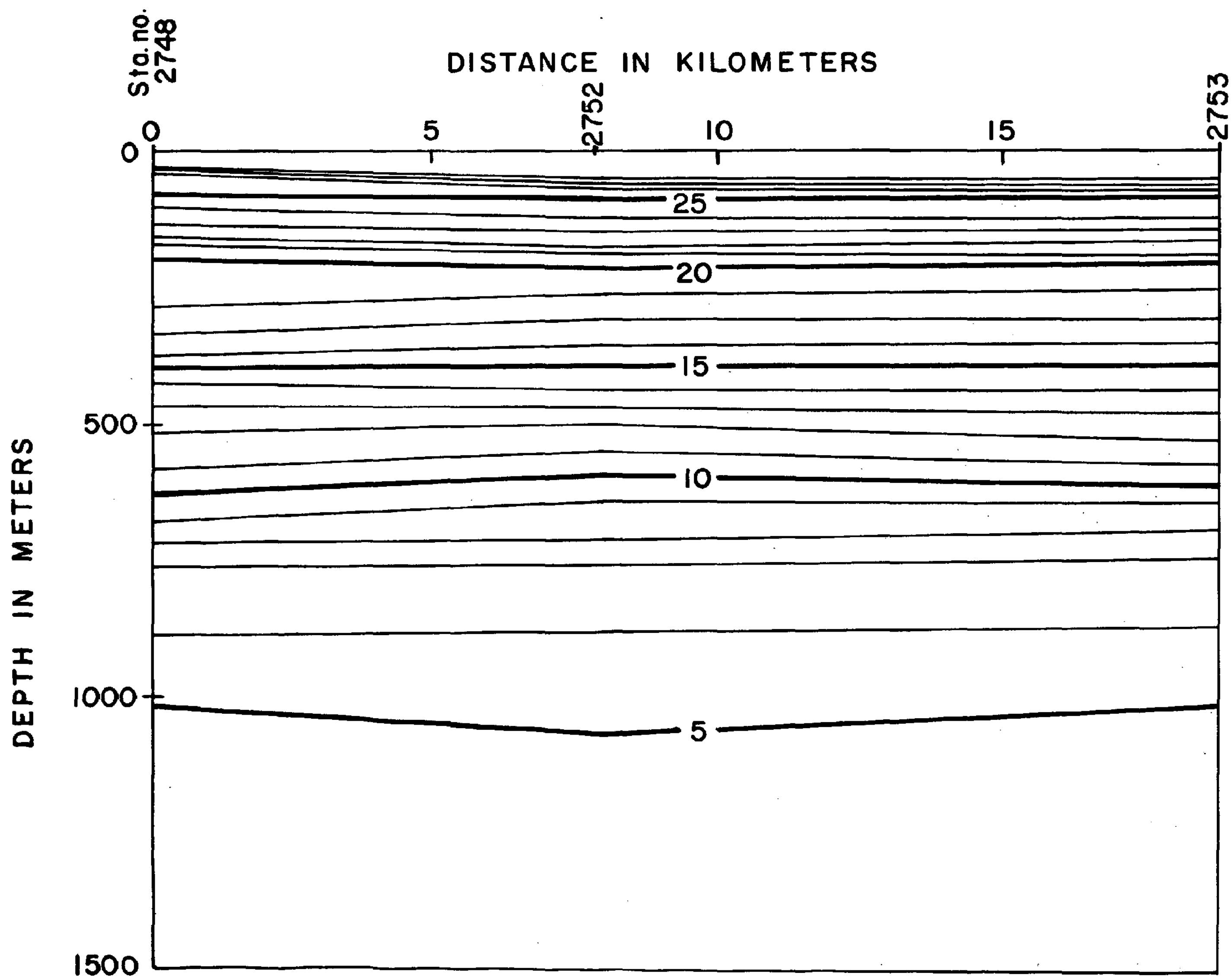


FIG. 49 TEMPERATURE SECTION FOR OTEC CRUISE #1 - SEPT. 1975

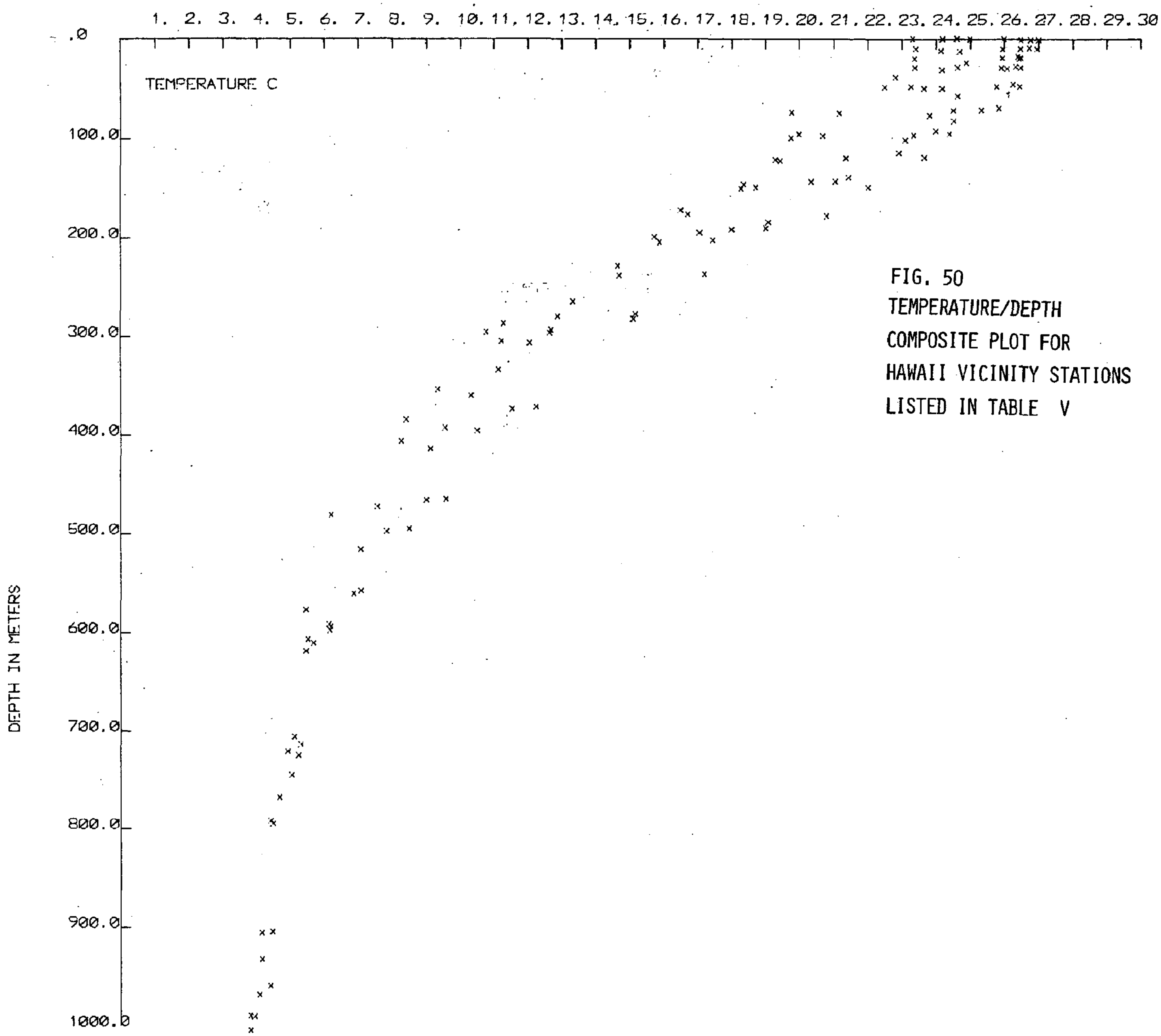


FIG. 50
TEMPERATURE/DEPTH
COMPOSITE PLOT FOR
HAWAII VICINITY STATIONS
LISTED IN TABLE V

The gradient of temperature versus depth is somewhat greater in the Hawaii area down to about 700 meters and the temperatures at 800 and 1000 meters are respectively 4.2° C and 3.5° C compared to about 6.2° C and 5.1° C at the Puerto Rico site.

II.3.3 Diurnal Variations

During the May 1976 cruise to the Point Tuna/Yabucoa site a survey of the diurnal variations in temperature was made to a depth of 750 meters using XBTs (expendable bathythermographs). 750 meter XBT probes were dropped every hour for a 24 hour period starting at 1650 hours on 10 May 1976. The XBT traces obtained are shown in Figure 51 in serial fashion. The figure has a common depth scale for all traces at the right. Temperatures may be read by orienting to the 20° C point indicated on each trace and using the temperature scale in the lower right corner of the figure (the scale is constant for the entire trace). Negligible variation is noted in the deep water except for slight changes which are associated with local shear and density gradients. These are scientifically interesting but of little importance to siting an OTEC plant. Of more importance are variations noted near the surface. Temperature variations in the mixed layer were relatively insignificant with the surface varying only from 26.2° C to 26.8° C and the point just above the discontinuity being a constant 26.2° $\pm$ 0.1° C. However, the depth of the mixed layer did vary significantly from a minimum depth of 40 meters to a maximum of 66 meters. This variation occurred on about a 12 hour cycle (semidiurnal) and is probably tidal in origin. Throughout the diurnal temperature survey water with a temperature of 24° C or higher existed to a minimum depth of 110 meters. The temperature at 750 meters was 7.0 $\pm$ 0.2° C throughout the 24 hour period.

II.4 <u>Salinity</u>

Figures 52 through 55 show the distribution of salinity with depth for each UPR OTEC cruise to the Point Tuna/Yabucoa site. Figure 56 is a composite plot of the same thing for all four cruises. These plots show essentially the same features as Figure 27 does for the PESCA serial station data except that surface salinities lower than 34.8 °/₀₀ were not observed at the OTEC site. However, surface salinities of < 34.5 °/₀₀ probably occurred at the site shortly after the September 1975 cruise during October and November. Surface mixed layer samples collected at the PESCA serial station on 8 November 1975 had salinities of 34.03°/₀₀ to 34.04 °/₀₀. These lower surface salinities during the period of September to January are associated with seasonal discharge from large South American river systems, e.g. the Amazon and Orinoco (Froelich and Atwood, 1976: see also section I.11).

Figure 57 is a temperature salinity (TS) plot for all UPR data collected at the Point Tuna/Yabucoa site. It shows the same features as the TS plot shown in Figure 24 for the PESCA serial station. The reader may refer to it and section I.9 for a discussion of the water cores represented. The only notable difference between Figures 24 and 57 is the higher percentage of salinities > 37 °/₀₀ in the salinity maximum (SUW)

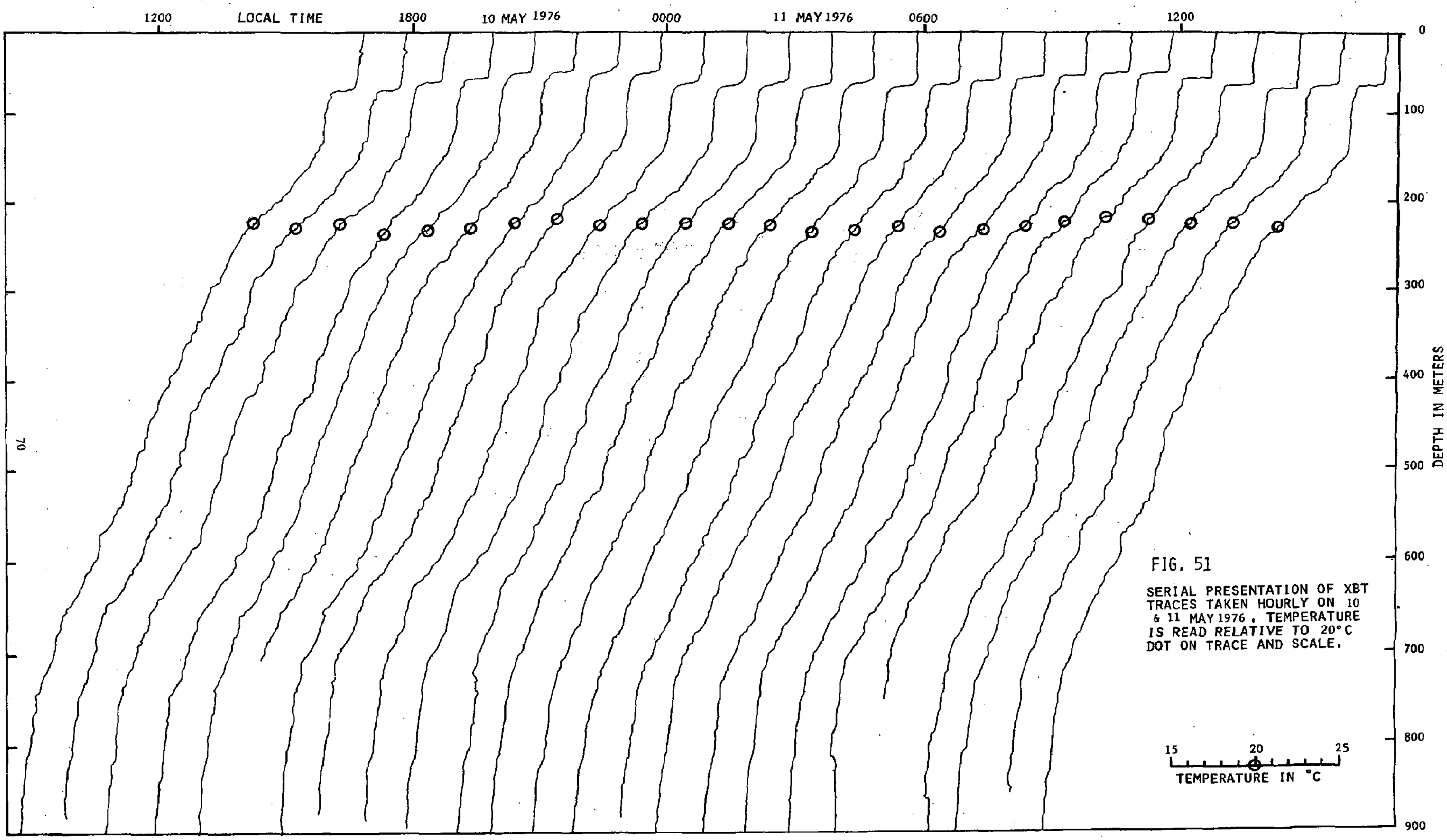


FIG. 51

SERIAL PRESENTATION OF XBT TRACES TAKEN HOURLY ON 10 & 11 MAY 1976, TEMPERATURE IS READ RELATIVE TO 20°C DOT ON TRACE AND SCALE.

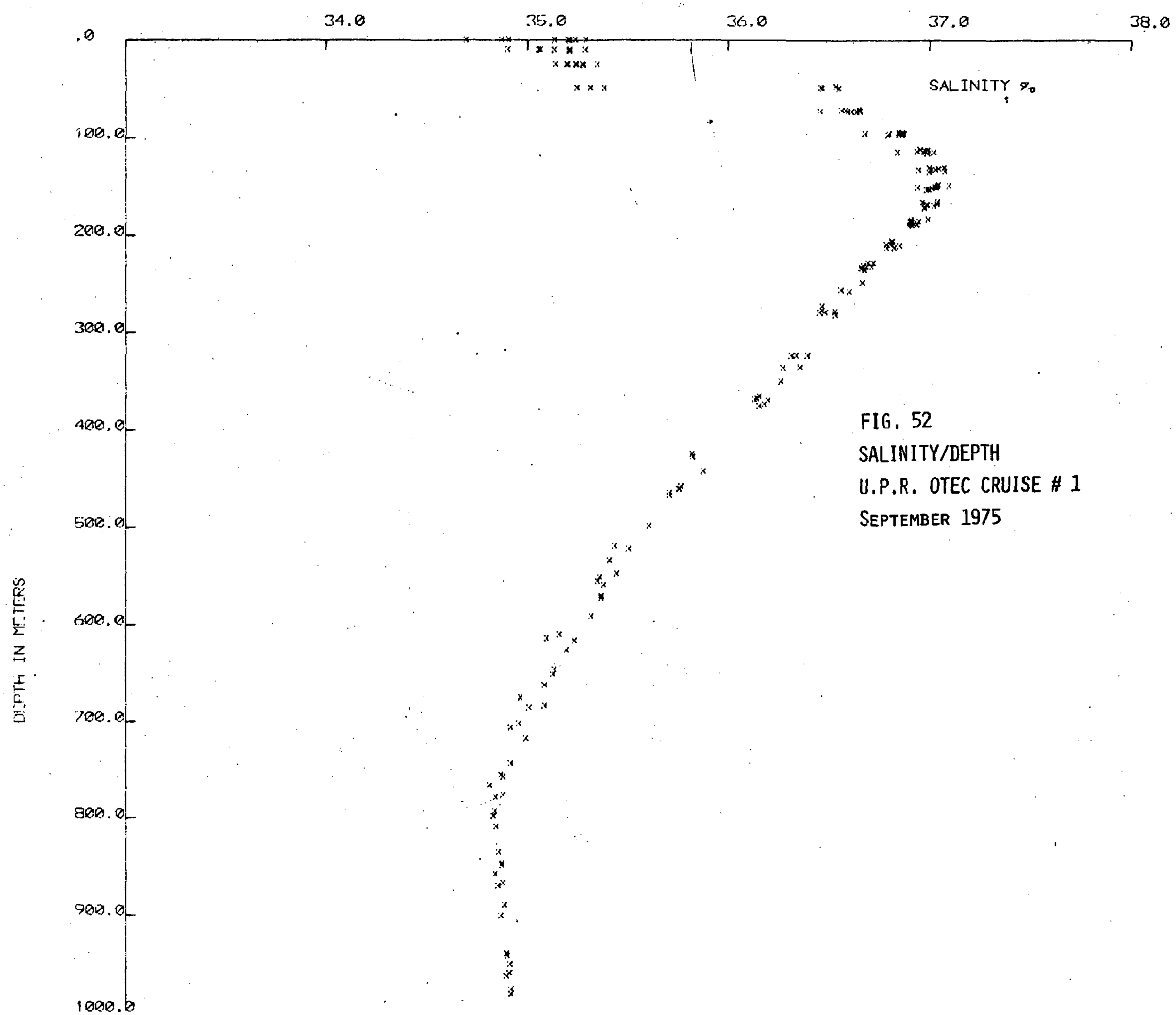


FIG. 52
SALINITY/DEPTH
U.P.R. OTEC CRUISE # 1
SEPTEMBER 1975

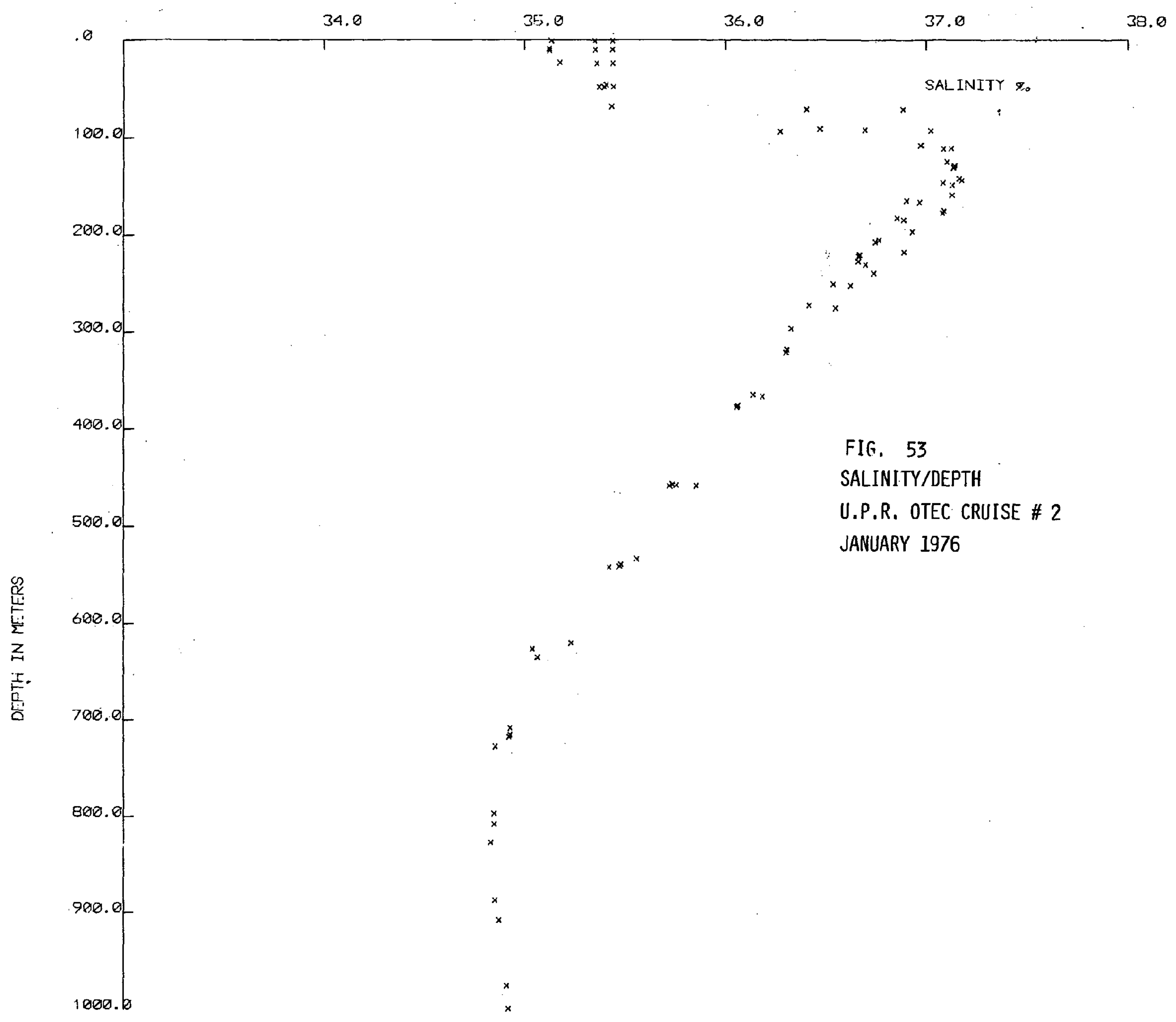


FIG. 53
SALINITY/DEPTH
U.P.R. OTEC CRUISE # 2
JANUARY 1976

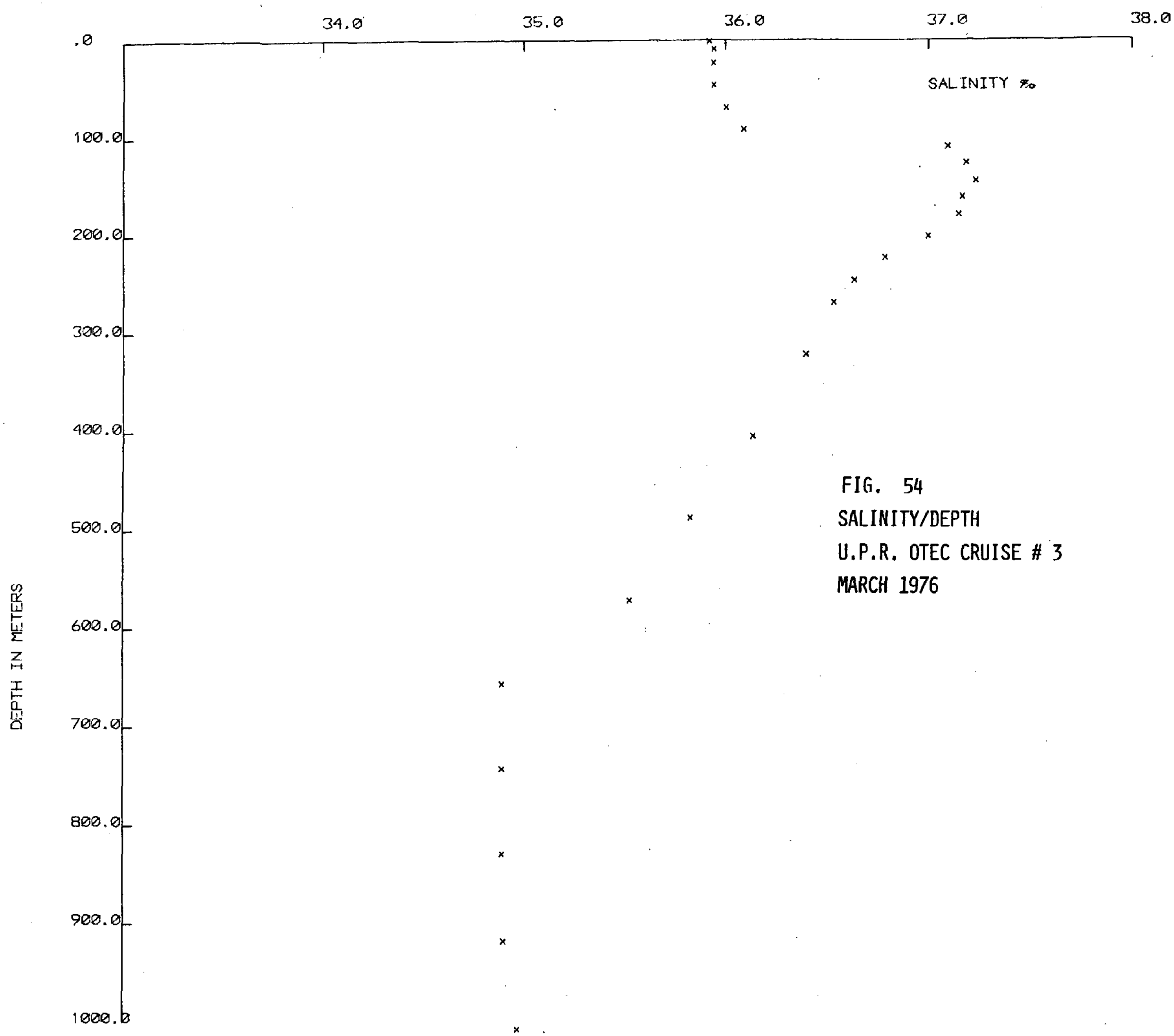


FIG. 54
SALINITY/DEPTH
U.P.R. OTEC CRUISE # 3
MARCH 1976

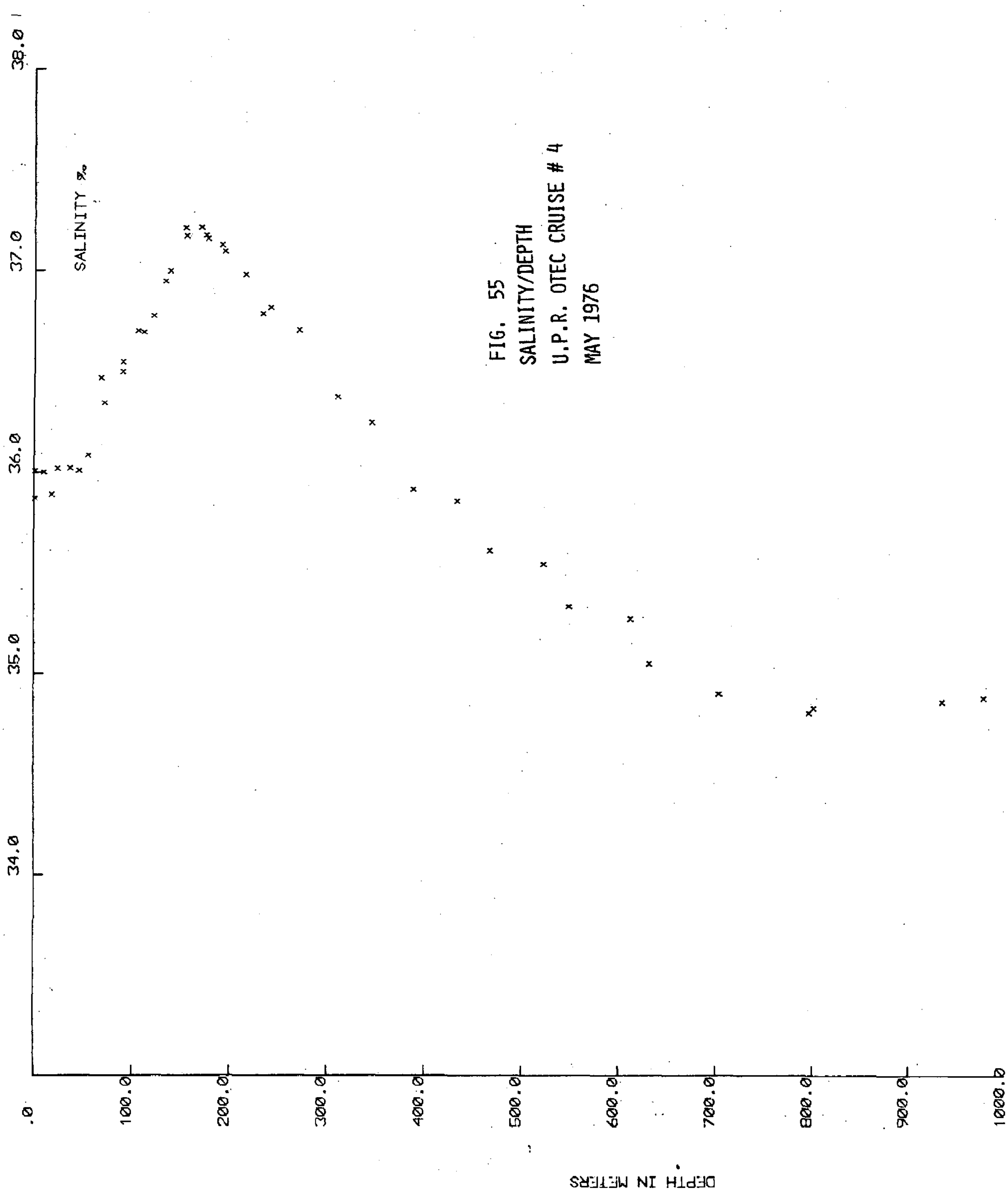


FIG. 55
SALINITY/DEPTH
U.P.R. OTEC CRUISE # 4
MAY 1976

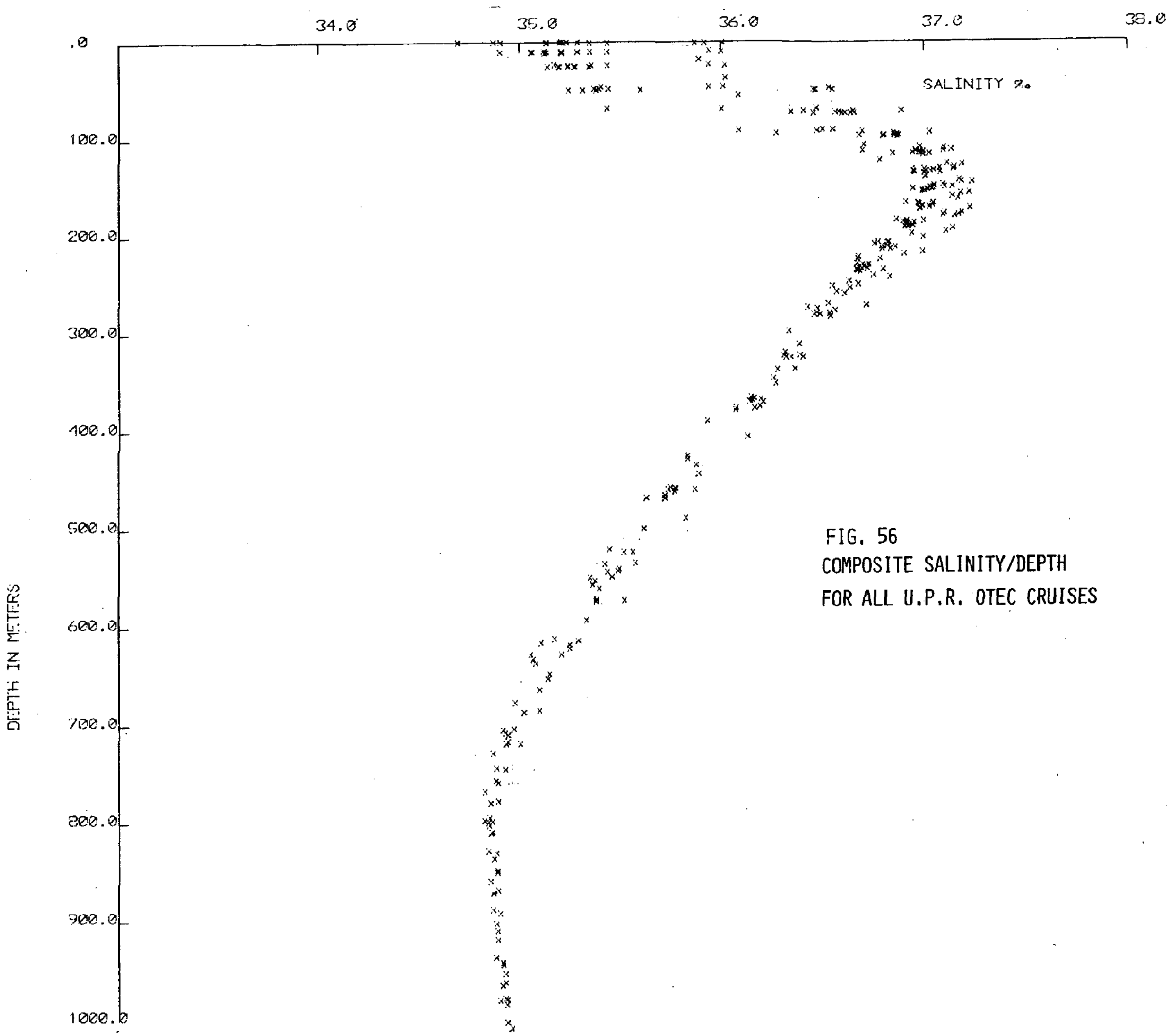


FIG. 56
COMPOSITE SALINITY/DEPTH
FOR ALL U.P.R. OTEC CRUISES

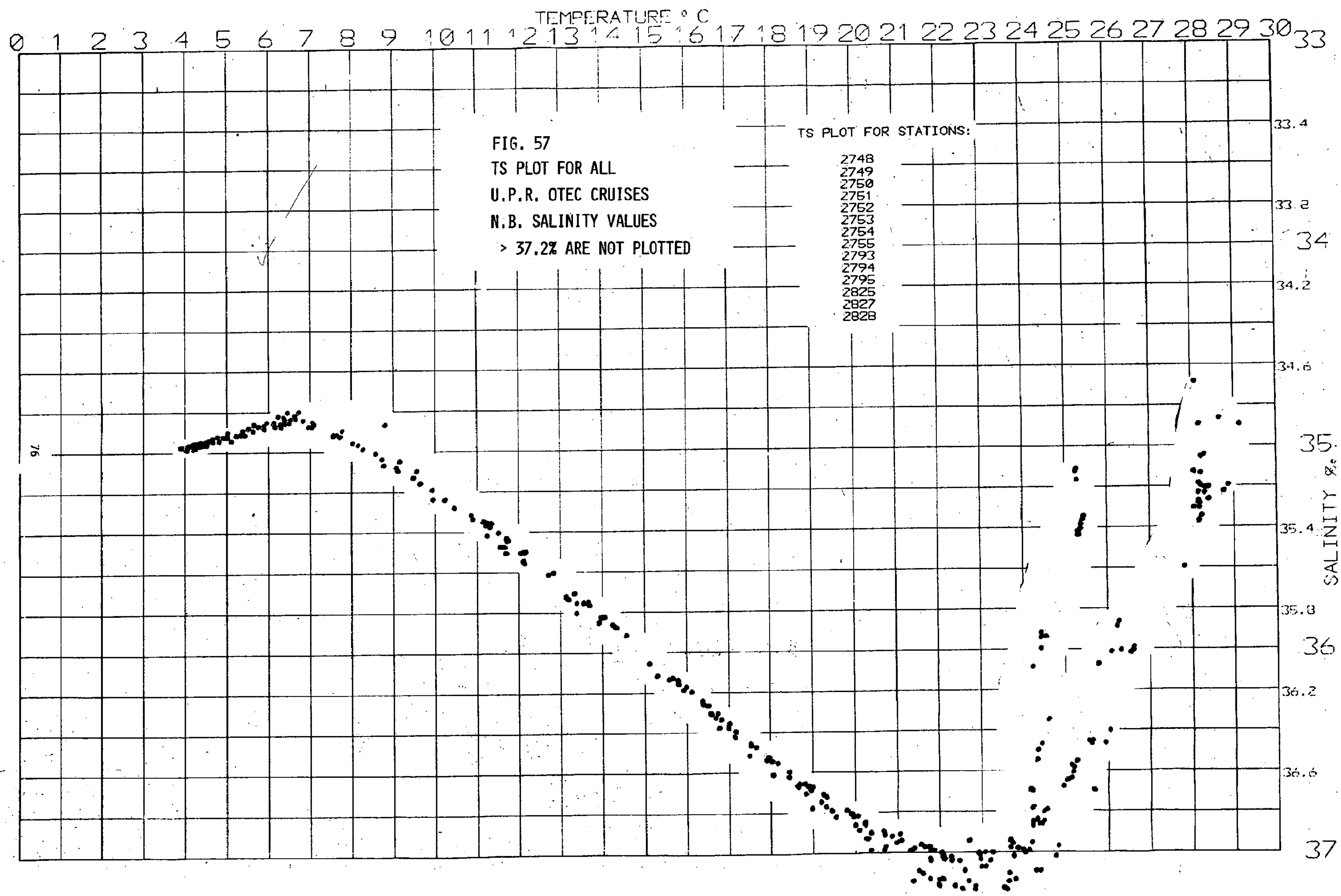


FIG. 57
TS PLOT FOR ALL
U.P.R. OTEC CRUISES
N.B. SALINITY VALUES
> 37.2‰ ARE NOT PLOTTED

at the OTEC site. This is due to two factors; (1) the OTEC site is some 90 miles closer to the origin of the SUW water and (2) in 1975 and 1976 this water core generally exhibited higher salinities.

II.5 Nutrients

During each UPR cruise to the Point Tuna/Yabucoa OTEC site samples were collected for phosphate, nitrate/nitrite and dissolved silicate. These were analyzed using the techniques described by Strickland and Parsons (1968) with modifications noted by Atwood (1974). The results of these analyses are represented in Figures 58 through 68. The profiles are typical of those for open tropical seas and no major difference from the results for the PESCA serial stations (described in section I.14) were noted. In general all nutrients were quite depleted in the near surface or photic zone due to removal by plankton which are produced there. The nutrients are more concentrated at deeper depths where sinking plankton detritus decays releasing the nutrients to the water. Maximum nutrient concentrations occur at close to the same depths as the oxygen minimums (see section II.6) reflecting the fact that the oxidation or decay of plankton partially depletes the oxygen at these depths as the nutrients are regenerated. The reader is referred to section I.14 for a discussion of biostimulation which might occur if these deep, nutrient rich waters are pumped to the surface by an OTEC plant. The following is a brief discussion of each of the nutrients analyzed for -

II.5.1 Phosphate

Phosphate versus depth plots for each UPR OTEC cruise are shown in Figures 58 through 61, and Figure 62 is a composite plot for all four cruises. At no time did phosphate values above 200 meters, i. e., in the photic zone, exceed 0.3 μ M. Values were highest in the September and January cruises, but, were very depleted in the March and May cruises. In September near surface values between 0.20 μ M and 0.25 μ M were found at stations 2748, 2755 and 2754 (see Figure 38 for locations). This may be due to some upwelling near shore and near Grappler Bank, however, neither stations 2751 nor 2753 exhibited similar high values. In January high values (0.20 - 0.25 μ M) were observed at stations 2793 and 2795 (see Figure 39). In March and May most values above 200 meters were zero,i.e., readings were equal to or less than those for the reagent blank used in the analysis.

Deep phosphate values were relatively constant throughout the year and most of the scatter below 300 meters in Figure 62 can be considered as analytical variation, the precision of the analysis being less as the phosphate level increases.

II.5.2 Nitrate/Nitrite

Due to the large volumes required, samples for nitrate and nitrite were collected only at the stations closest to Point Tuna (Stations 2748, 2793, 2825 and 2827, see Figures 38 to 41). We regard this

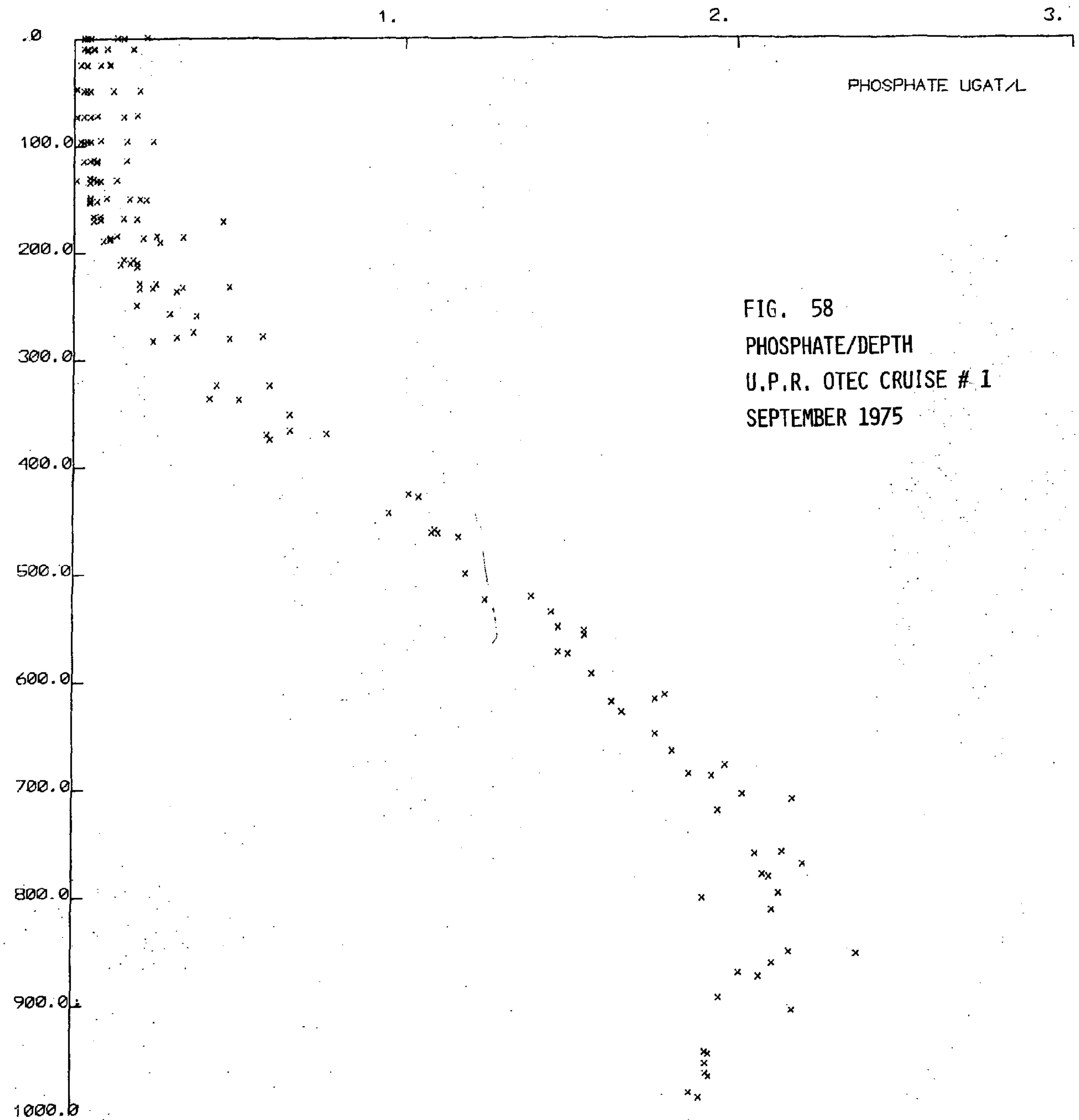


FIG. 58
PHOSPHATE/DEPTH
U.P.R. OTEC CRUISE # 1
SEPTEMBER 1975

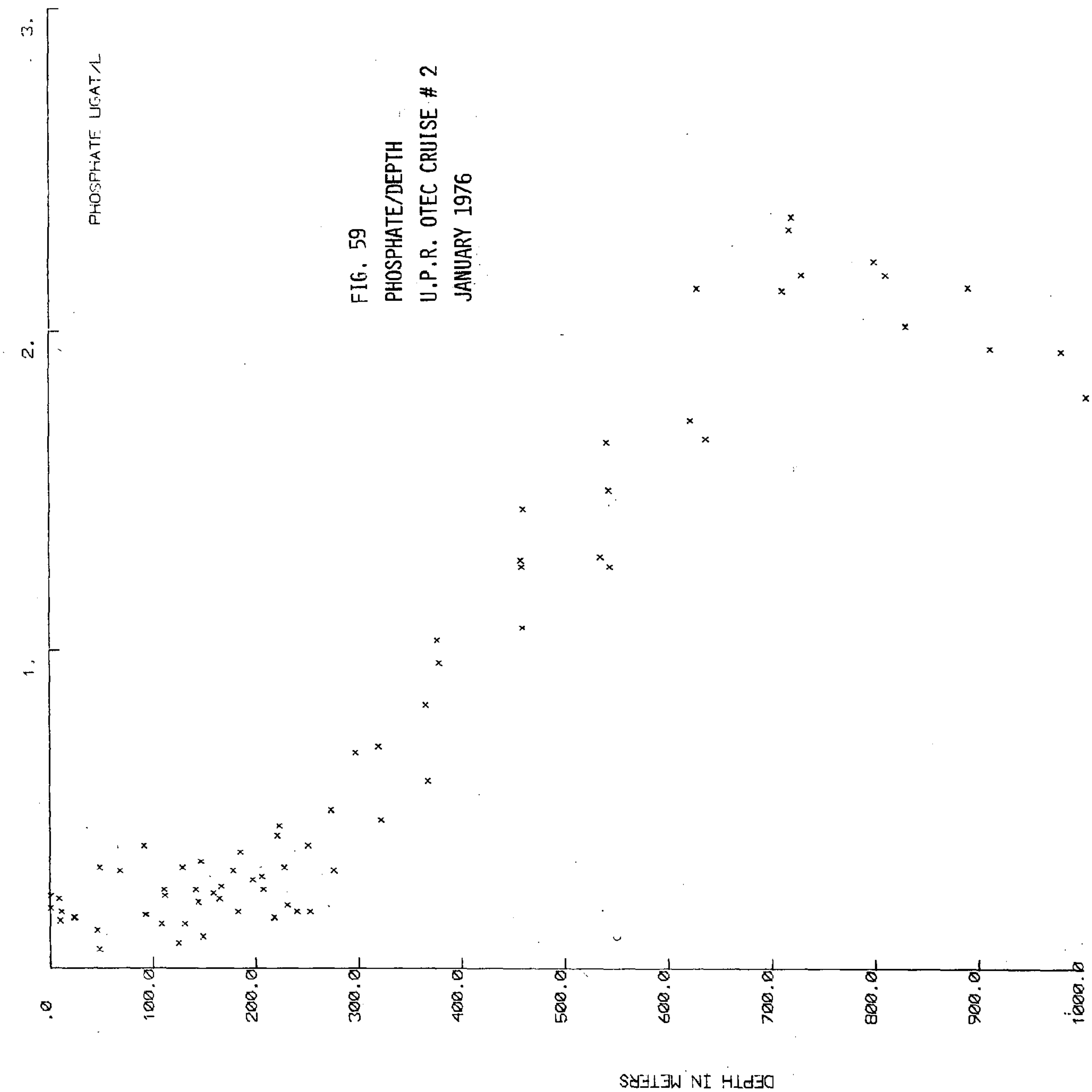


FIG. 59
PHOSPHATE/DEPTH
U.P.R. OTEC CRUISE # 2
JANUARY 1976

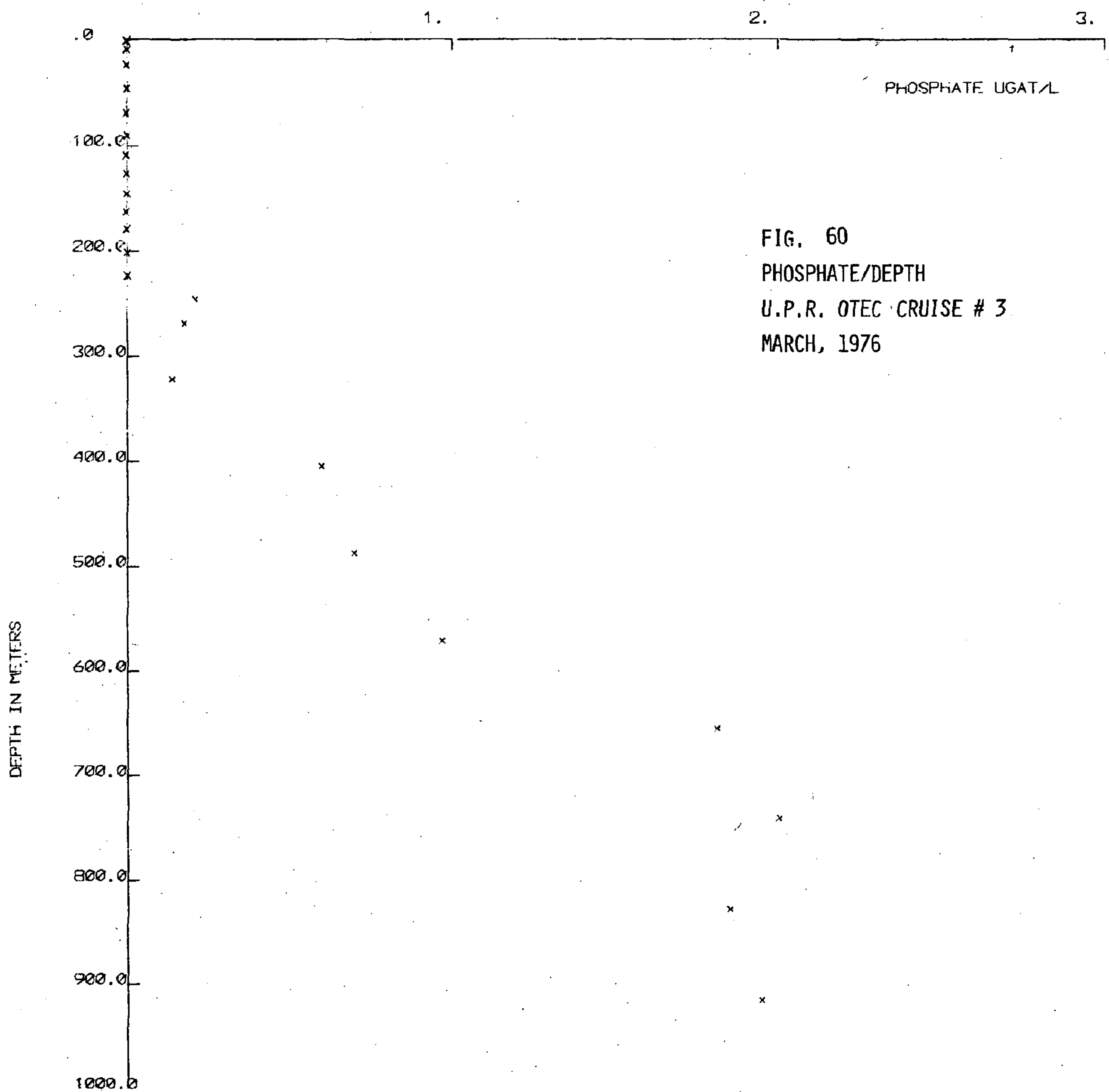


FIG. 60
PHOSPHATE/DEPTH
U.P.R. OTEC CRUISE # 3
MARCH, 1976

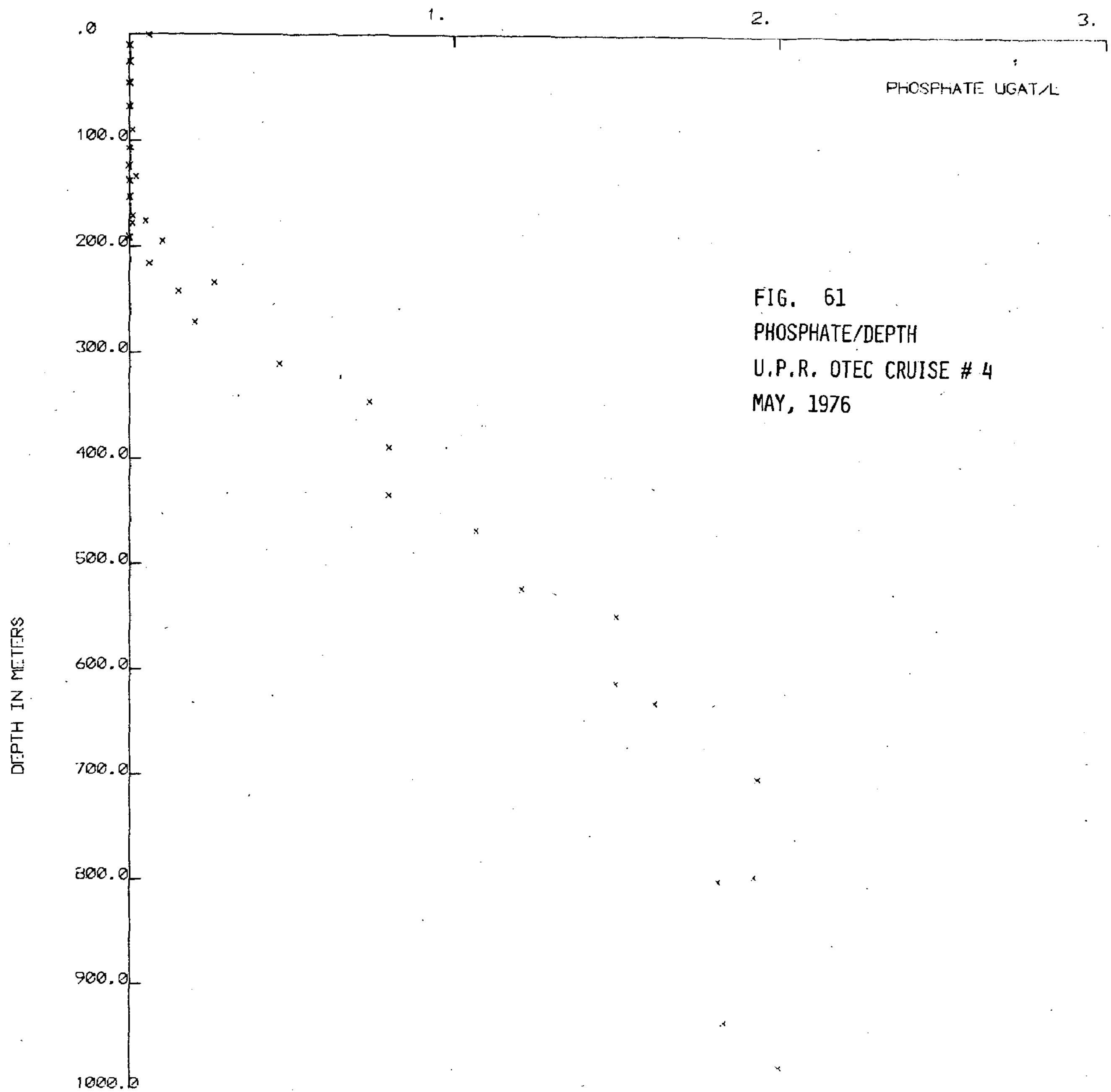


FIG. 61
PHOSPHATE/DEPTH
U.P.R. OTEC CRUISE # 4
MAY, 1976

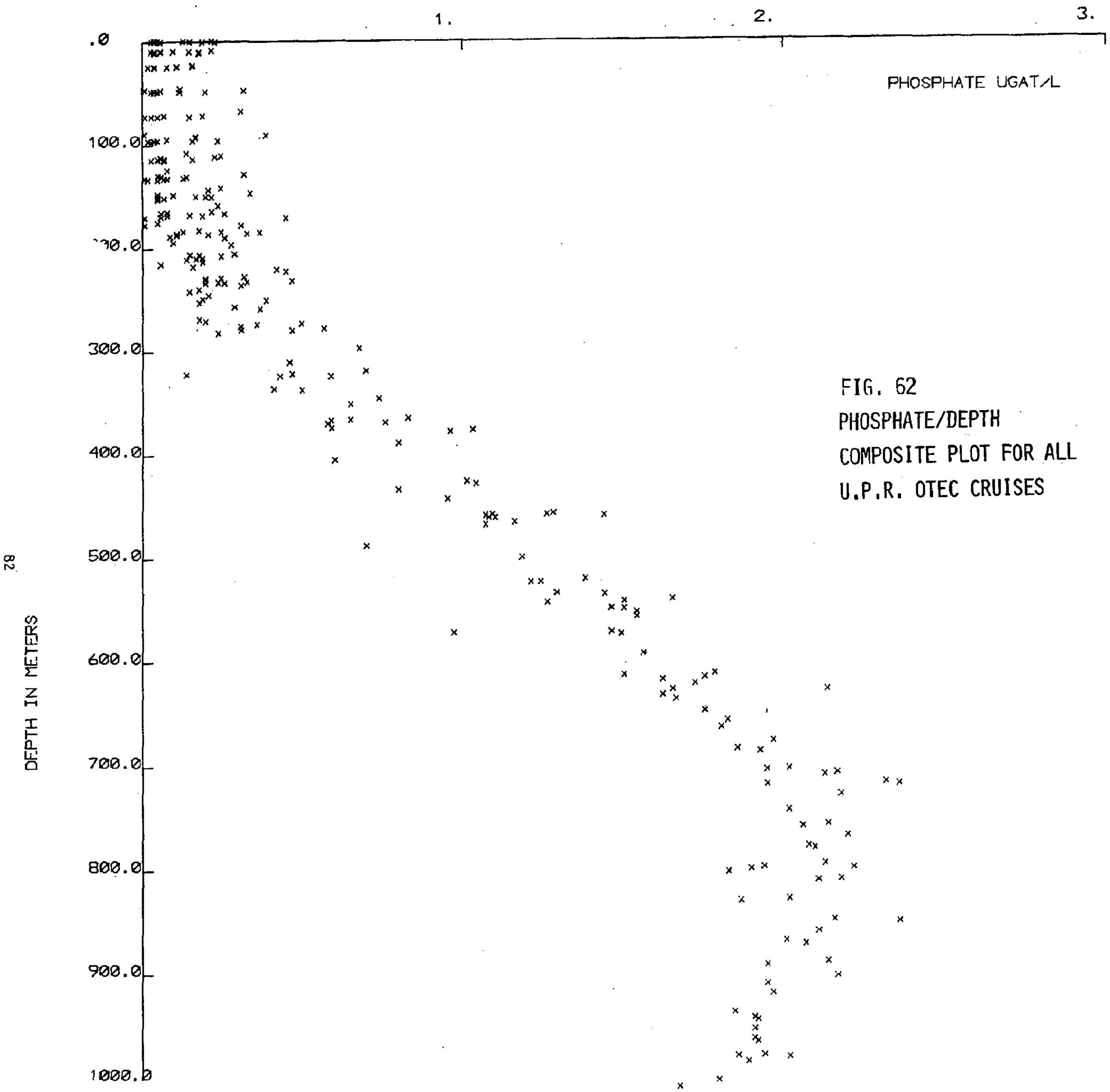


FIG. 62
PHOSPHATE/DEPTH
COMPOSITE PLOT FOR ALL
U.P.R. OTEC CRUISES

specific location as the most favorable one for siting a prototype OTEC plant.

Nitrate values were all < 0.05 μ M and generally < 0.03 μ M. Highest values were found at the bottom of the mixed layer or between 75 and 150 meters.

The results for the nitrate analyses are given in Figure 63 for all cruises and a mean nitrate versus depth curve is drawn. The curve is very similar to that for the PESCA serial station data shown in Figure 36. Photic zone nitrate values at the OTEC site were lowest in the September and January cruises (0.2 to 1.5 μ M) and highest in May (1 to 4 μ M) with March intermediate. This is opposite from the phosphate data which was highest in September and January and depleted in March and May. This would indicate that plankton productivity and/or upwelling are not the only mechanisms affecting nutrient concentrations in the photic zone. If these were the only mechanisms the N : P ratio would stay relatively constant.

Comparison of Figures 62 and 63 shows that the N : P at the nutrient maximum is almost exactly 16 : 1 indicating that the nutrients in the deep water are ideally proportioned as a planktonic fertilizer (see section I.14).

II.5.3 Silicate

Figures 64 through 67 show the distribution of dissolved silicate with depth for each of the cruises to the Point Tuna/Yabucoa OTEC site. Figure 68 is a composite plot for all four cruises. As with the other nutrients the distribution of dissolved silicate at the OTEC site is not basically different from that at the PESCA serial station (see Figure 35) and no significant variations were noted throughout the study.

II.6 Oxygen

Figures 69 through 72 are plots of dissolved oxygen versus depth for each of the four UPR cruises to the Point Tuna/Yabucoa OTEC site. Figure 73 is a composite plot of the same data for all four cruises. The data is essentially identical to that shown in Figure 37 for the PESCA serial station data. With the exception of the slightly higher surface values observed during the May 1976 OTEC cruise very little variation in the oxygen profile is noted. There is ample oxygen at all depths to support all forms of marine life. The features of the oxygen profile as they relate to their causes and the water cores present is discussed in section I.15. The minimum in the curve between 600 and 800 meters is also discussed under nutrients in sections I.14 and II.5

II.7 Geostrophic Currents

We have attempted to determine the magnitude of near surface (upper 500 meters) currents at the OTEC site using the geostrophic method. The results of these calculations for Cruise No. 1 in September 1975 are

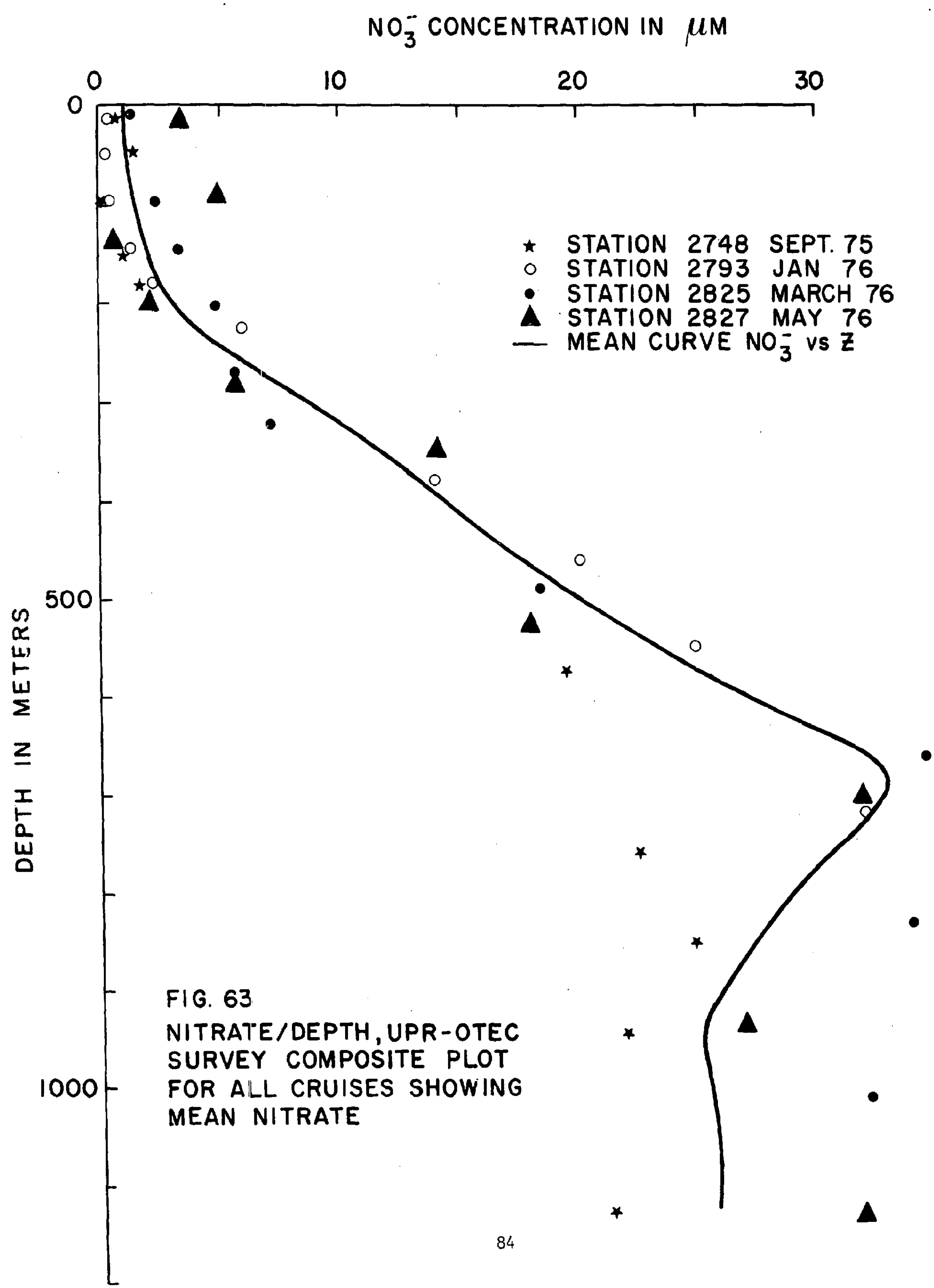


FIG. 63
NITRATE/DEPTH, UPR-OTEC SURVEY COMPOSITE PLOT FOR ALL CRUISES SHOWING MEAN NITRATE

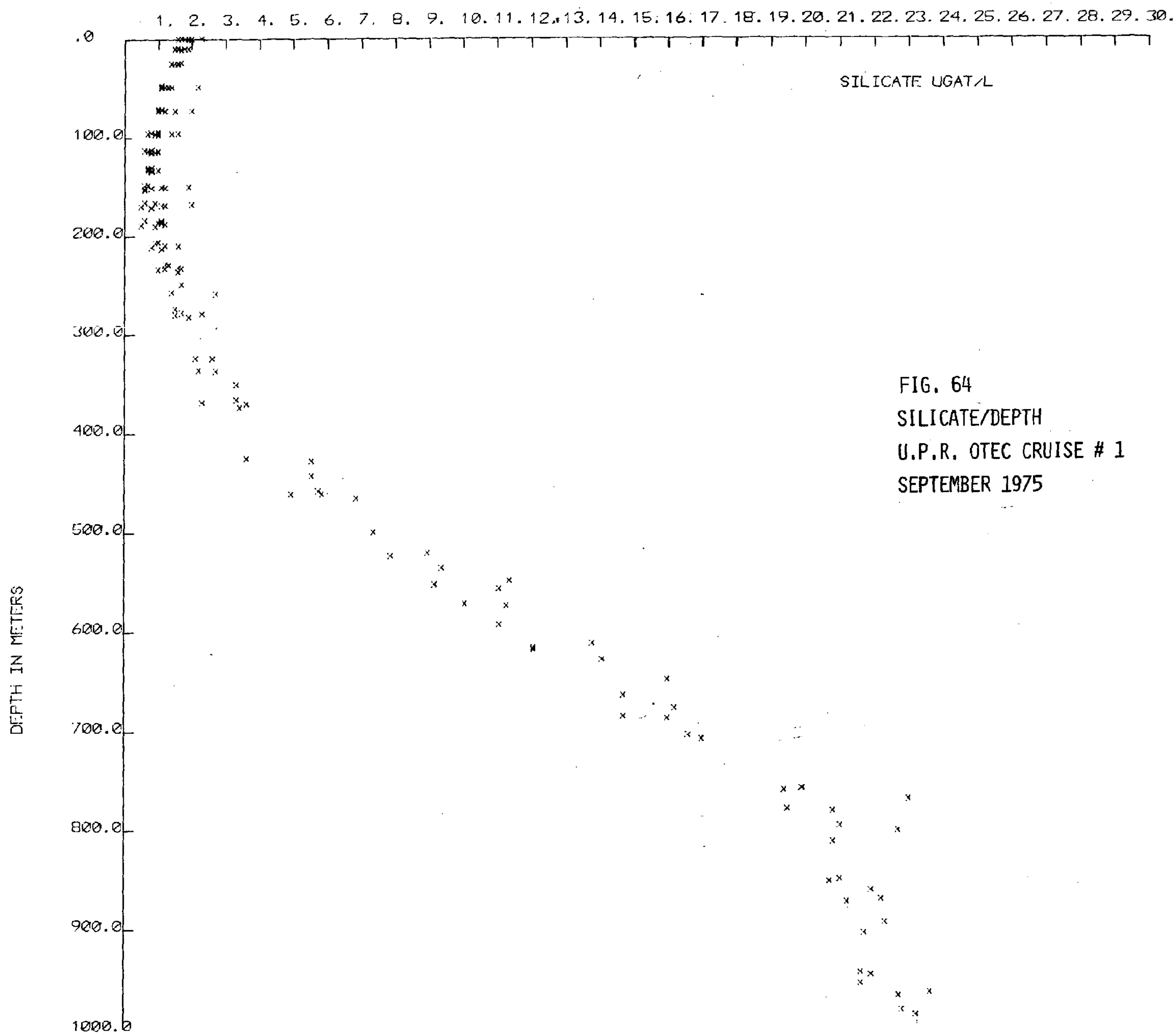


FIG. 64
SILICATE/DEPTH
U.P.R. OTEC CRUISE # 1
SEPTEMBER 1975

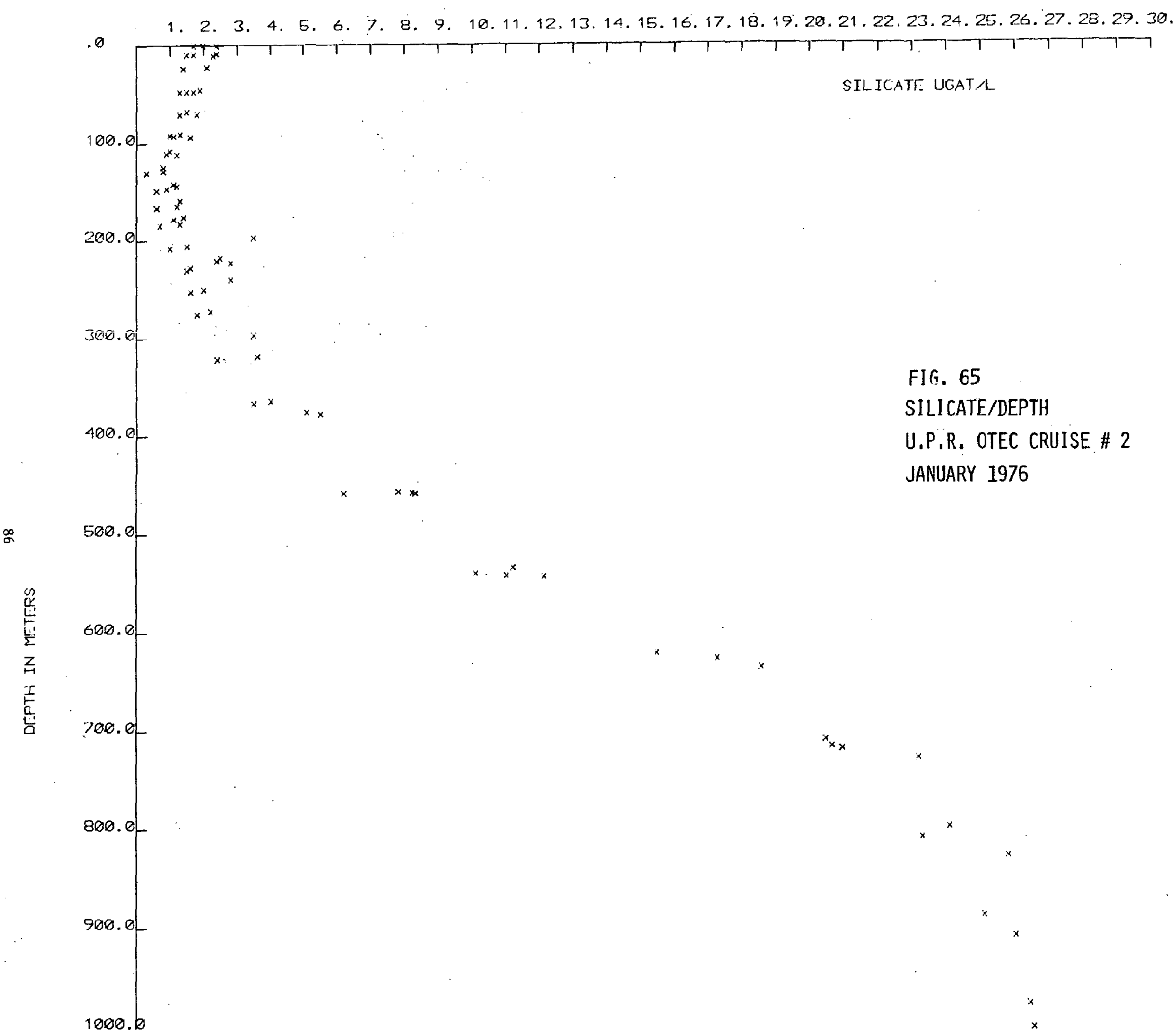


FIG. 65
SILICATE/DEPTH
U.P.R. OTEC CRUISE # 2
JANUARY 1976

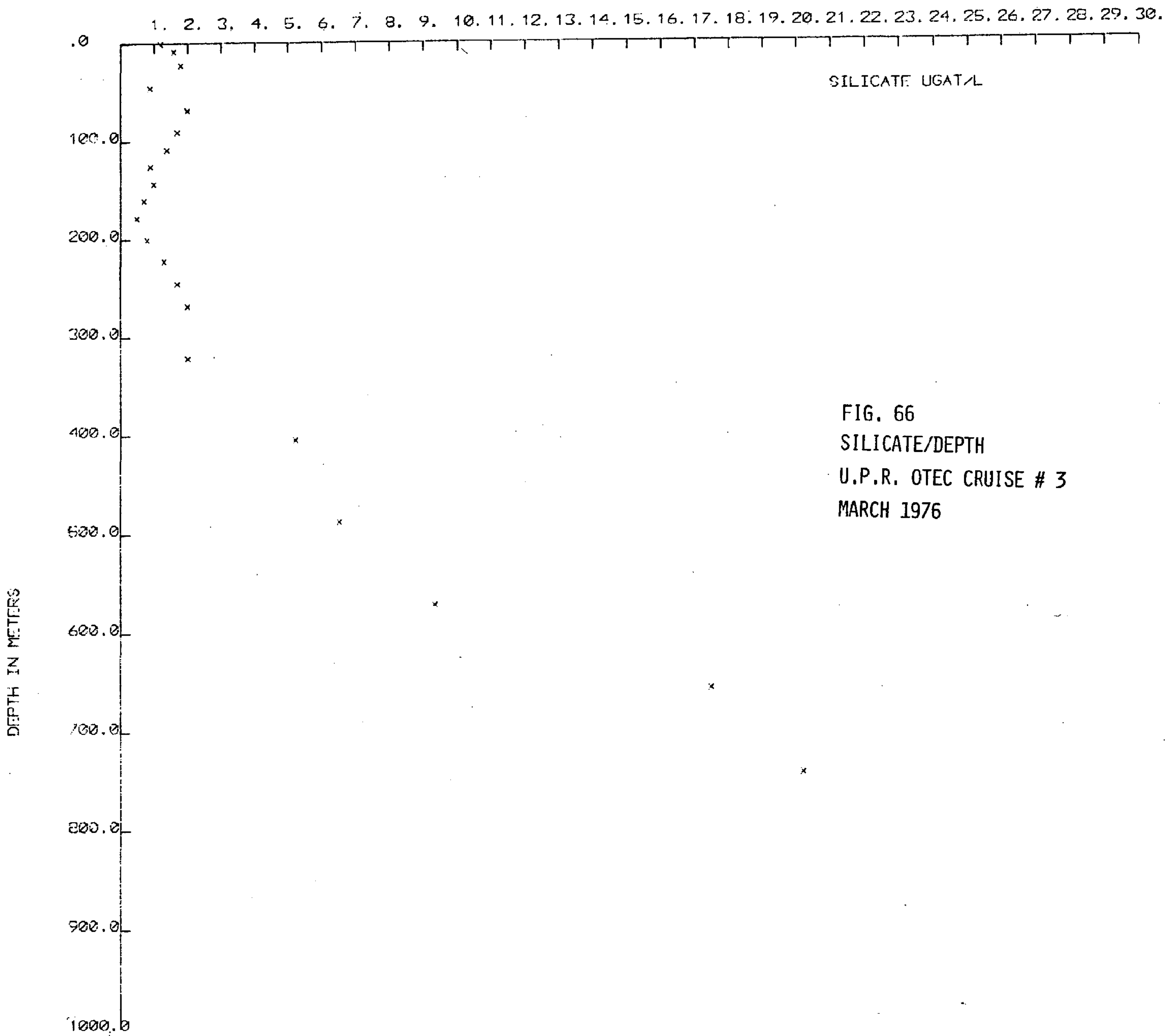


FIG. 66
SILICATE/DEPTH
U.P.R. OTEC CRUISE # 3
MARCH 1976

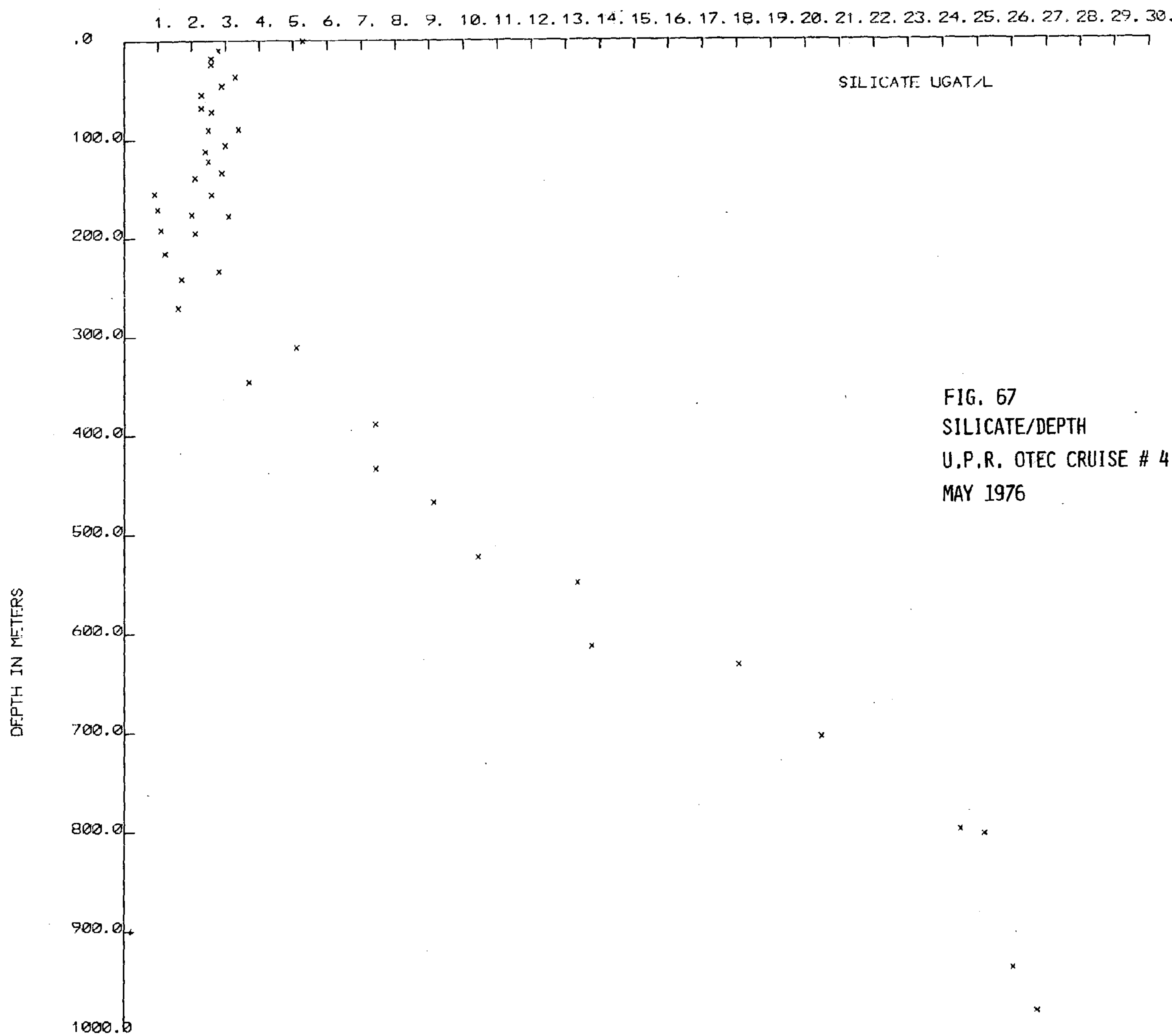


FIG. 67
SILICATE/DEPTH
U.P.R. OTEC CRUISE # 4
MAY 1976

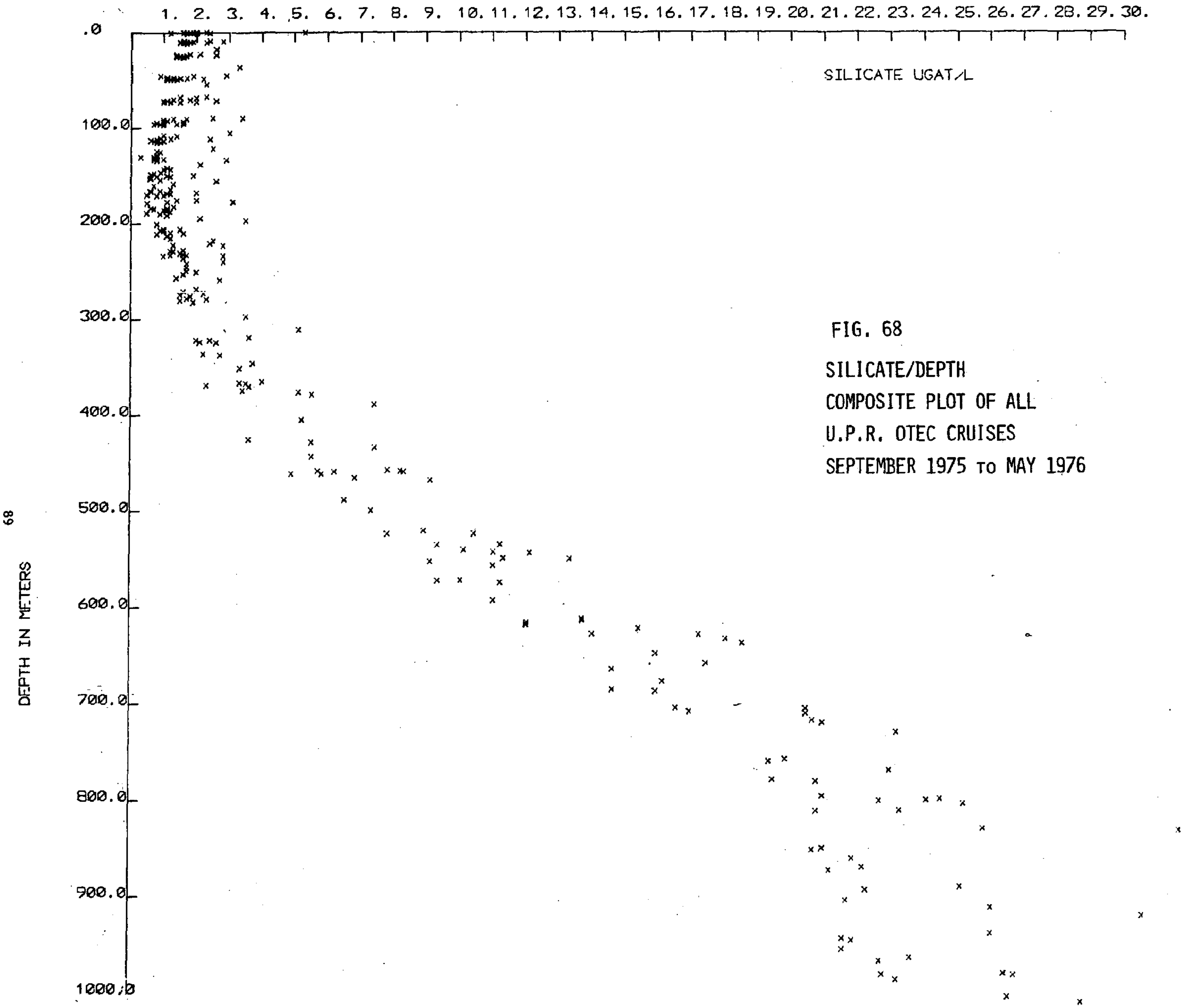


FIG. 68

SILICATE/DEPTH
COMPOSITE PLOT OF ALL
U.P.R. OTEC CRUISES
SEPTEMBER 1975 TO MAY 1976

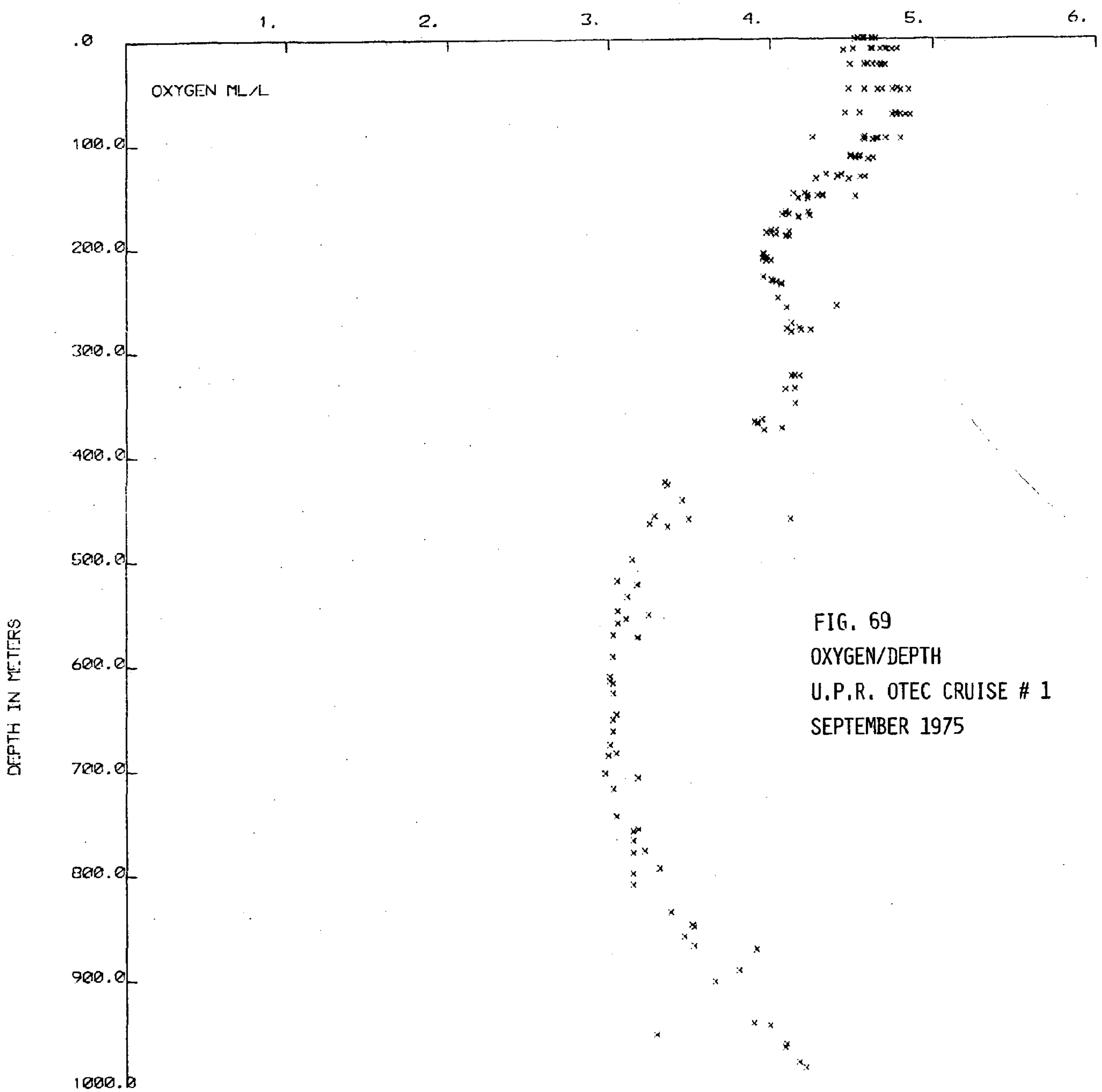


FIG. 69
OXYGEN/DEPTH
U.P.R. OTEC CRUISE # 1
SEPTEMBER 1975

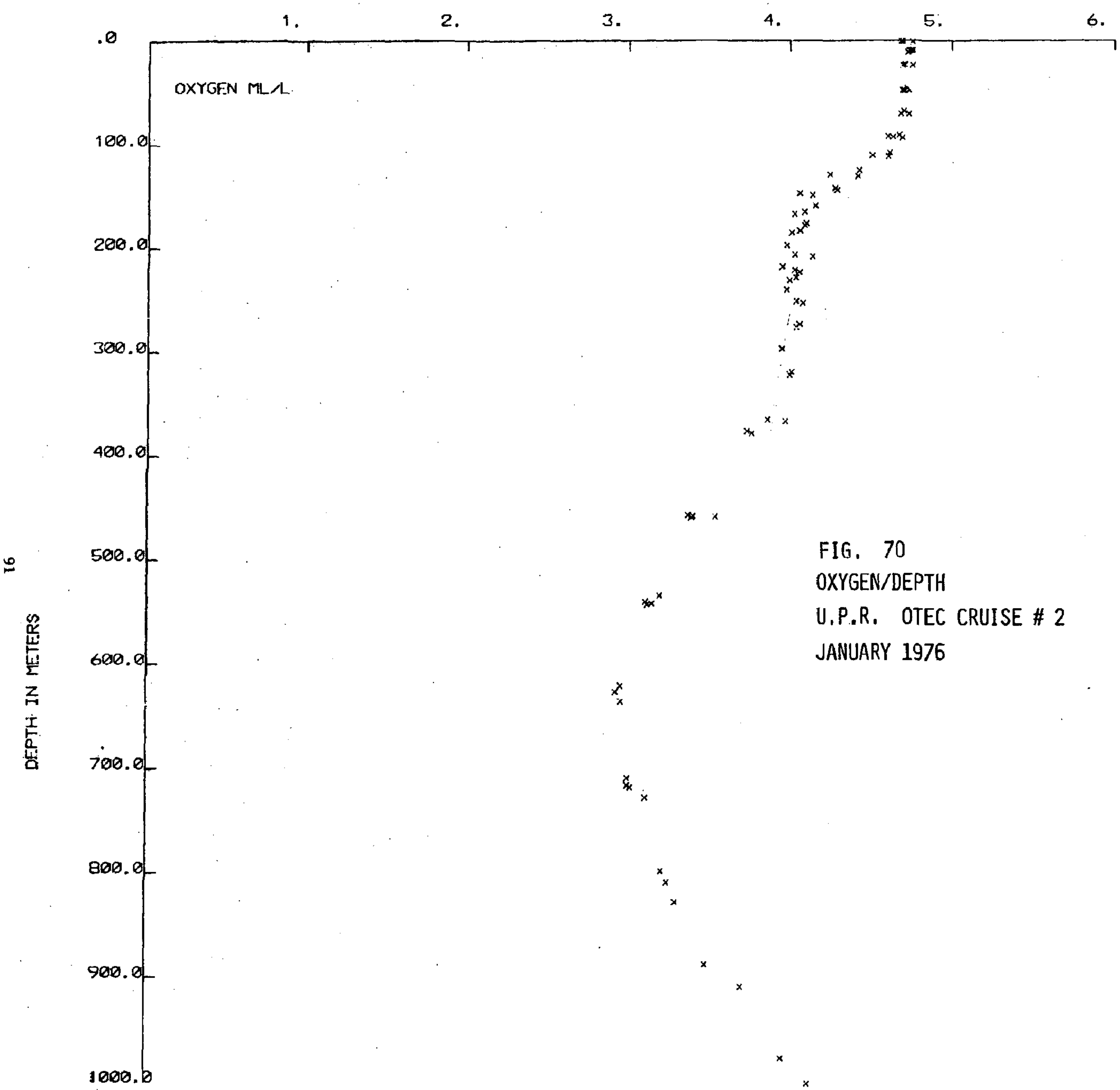


FIG. 70
OXYGEN/DEPTH
U.P.R. OTEC CRUISE # 2
JANUARY 1976

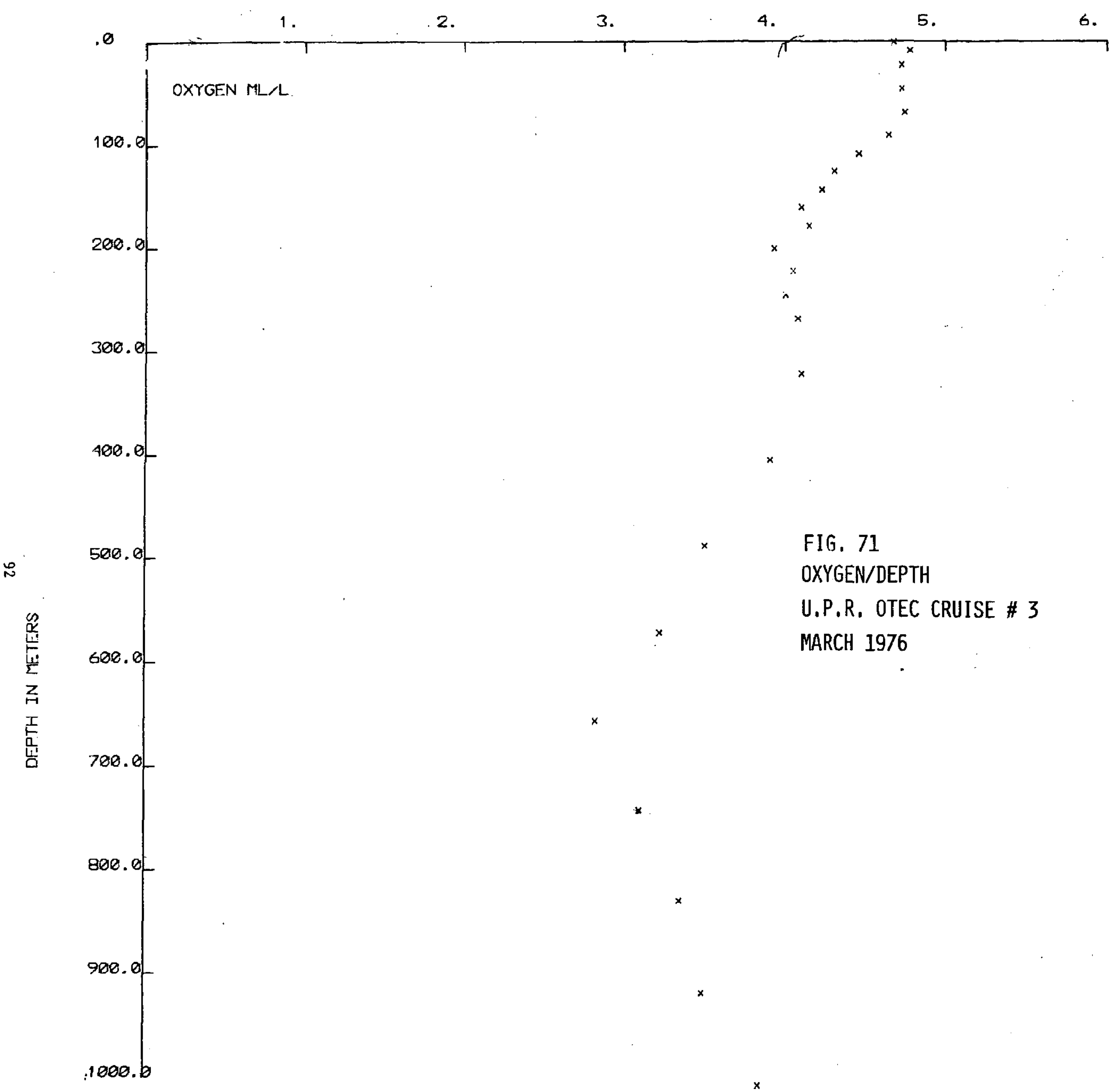


FIG. 71
OXYGEN/DEPTH
U.P.R. OTEC CRUISE # 3
MARCH 1976

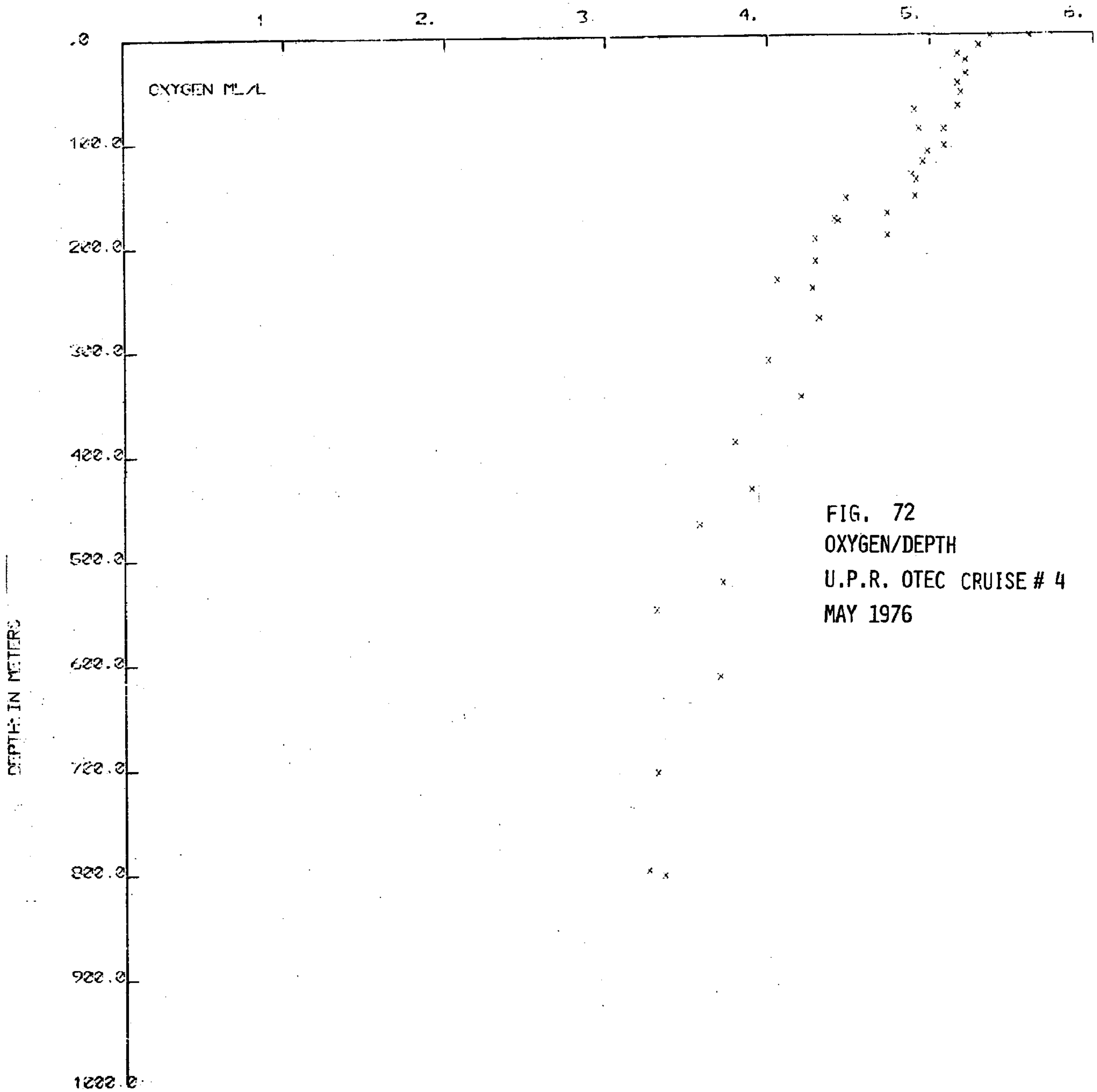


FIG. 72
OXYGEN/DEPTH
U.P.R. OTEC CRUISE # 4
MAY 1976

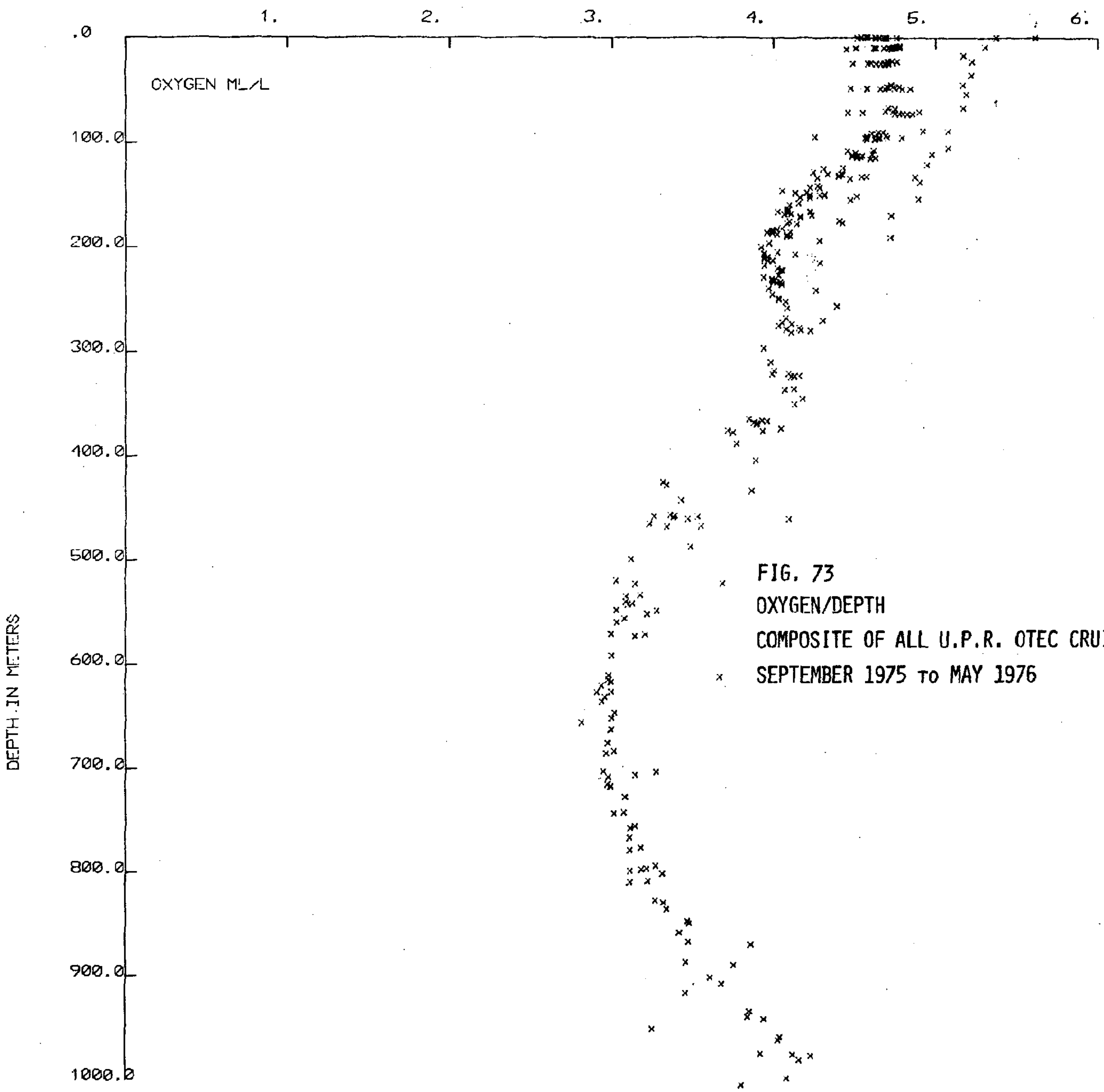


FIG. 73
OXYGEN/DEPTH
COMPOSITE OF ALL U.P.R. OTEC CRUISES
SEPTEMBER 1975 TO MAY 1976

given in Tables 7 and 8 (see Figure 38 for station locations. Unfortunately the geostrophic method is most suited to the study of meso-scale circulation, and is at its limits of accuracy when stations are only 20 km apart, so the results of the calculations presented in Tables 7 and 8 should be interpreted with caution. (Note that the zero velocity at 1000 meters is an assumption necessary for calculation, and is not an observation).

TABLE VII

GEOSTROPHIC VELOCITIES AT THE YABUCOA SITE
CRUISE # 1
(See Location Map, Fig. 38)

Distance between 2751 and 2749 = 20.21 km   Mean latitude = 17.91
Maximum depth is at Station 2749 and is 1000 meters. Dynamic height difference between Station 2751 and Station 2749 is -0.019 dynamic meters at 1000 meters

Depth Z	Volume Transport above Z	Velocity at Z	Volume Transport Z2-Z1
0	0.00	-21.0	
			-0.14
50	-0.14	- 7.7	
			0.03
100	-0.12	13.2	
			0.19
200	0.07	5.5	
			0.11
300	0.18	5.5	
			0.10
400	0.28	4.4	
			0.04
500	0.33	- 0.0	
			-0.03
600	0.30	- 3.3	
			-0.09
700	0.21	- 5.5	
			-0.09
800	0.12	- 3.3	
			-0.02
900	0.09	1.1	
			0.01
1000	0.11	0.0	
Meters	Megatons/sec	CM/sec	Megatons/sec

Note positive values denote westerly flow and negative values easterly flow

TABLE VIII

GEOSTROPHIC VELOCITIES AT THE YABUCOA SITE
CRUISE # 1
(See Location Map, Fig. 38)

Distance between 2748 and 2753 = 19.04 km Mean latitude = 17.88
Maximum depth is at Station 2753 and is 1000 meters. Dynamic height difference between Station 2748 and Station 2753 is -0.036 dynamic meters at 1000 meters.

Depth Z	Volume Transport above Z	Velocity at Z	Volume Transport Z2-Z1
0	0.00	-42.2	
			-0.26
50	-0.26	-11.7	
			0.02
100	-0.24	15.2	
			0.35
200	0.11	21.1	
			0.32
300	0.43	12.9	
			0.20
400	0.63	8.2	
			0.16
500	0.79	8.2	
			0.15
600	0.93	7.0	
			0.09
700	1.02	2.3	
			0.06
800	1.08	3.5	
			0.06
900	1.13	2.3	
			0.02
1000	1.16	0.0	
Meters	Megatons/sec	CM/sec	Megatons/sec

Note positive values denote westerly flow and negative values easterly flow

Both calculations show an eastwards flow at the surface over a slow subsurface westwards flow, degenerating to random noise at 500 meters, below which depth the values are meaningless. About all that can be said is that at the time of the survey easterly surface velocities in the order of 1/3 to 1/2 knot were indicated between 0 and 50 meters with a reversal at about 100 meters to westerly flow of less than 1/3 knot. Since the stations were taken over a three day period this is an "average" condition.

PART III: CONSIDERATION OF OTHER SITES NEAR PUERTO RICO

Prior to submission of our original proposal and during the historical data survey reported herein we considered other possible OTEC sites near Puerto Rico with the conclusion that the Point Tuna site was the best site oceanographically. One other site which has some merit is off the Northwest coast of Puerto Rico near the town of Aguadilla and the inactive Ramey Air Force Base. Due to the real estate available at Ramey this site could have potenials other than strict oceanographic considerations. The following are some comments pertinent to this site.

(i) Bathymetry. In general the west coast is shallow and only at Aguadilla does a deep tongue protrude shoreward. Even so, depths of 1000 meters are only found 10 km (6 miles) NW from shore. (C & GS Chart 920).

(ii) Δ T Profiles. Little temperature data is available, but the south coast is likely to have both a more favorable surface water and a better rate of change of temperature with depth because of the geostrophic tilting effect mentioned in this report (sections I.10 and I.13). Figure 74 compares Δ T profiles off the South coast and off Aguadilla for comparable times of year.

(iii) "Accessibility in all weathers" is doubtful. Quoting from the Environmental Guide for the Mona Passage Area by NOAA, June, 1974, "Moderate or rough seas also develop at times in winter when the northeast trades become strong. There is a considerable increase in swell during the period December to March, due to the increased strength of the northeast trades at this time of the year. This is the season of 'rollers' when series of huge swells are liable to appear at any time. The rollers are very probably caused by gales further north over the Atlantic." (p. 14) "Waves of 20 feet or more have been observed for all months." (Op. cit. p. 25)

(iv) Oceanographically the Yabucoa site is more favorable. A short term advantage in terms of ready-to-use housing may be available at Ramey, but, if the plant is designed to serve for fifty to one hundred years, such considerations are minor

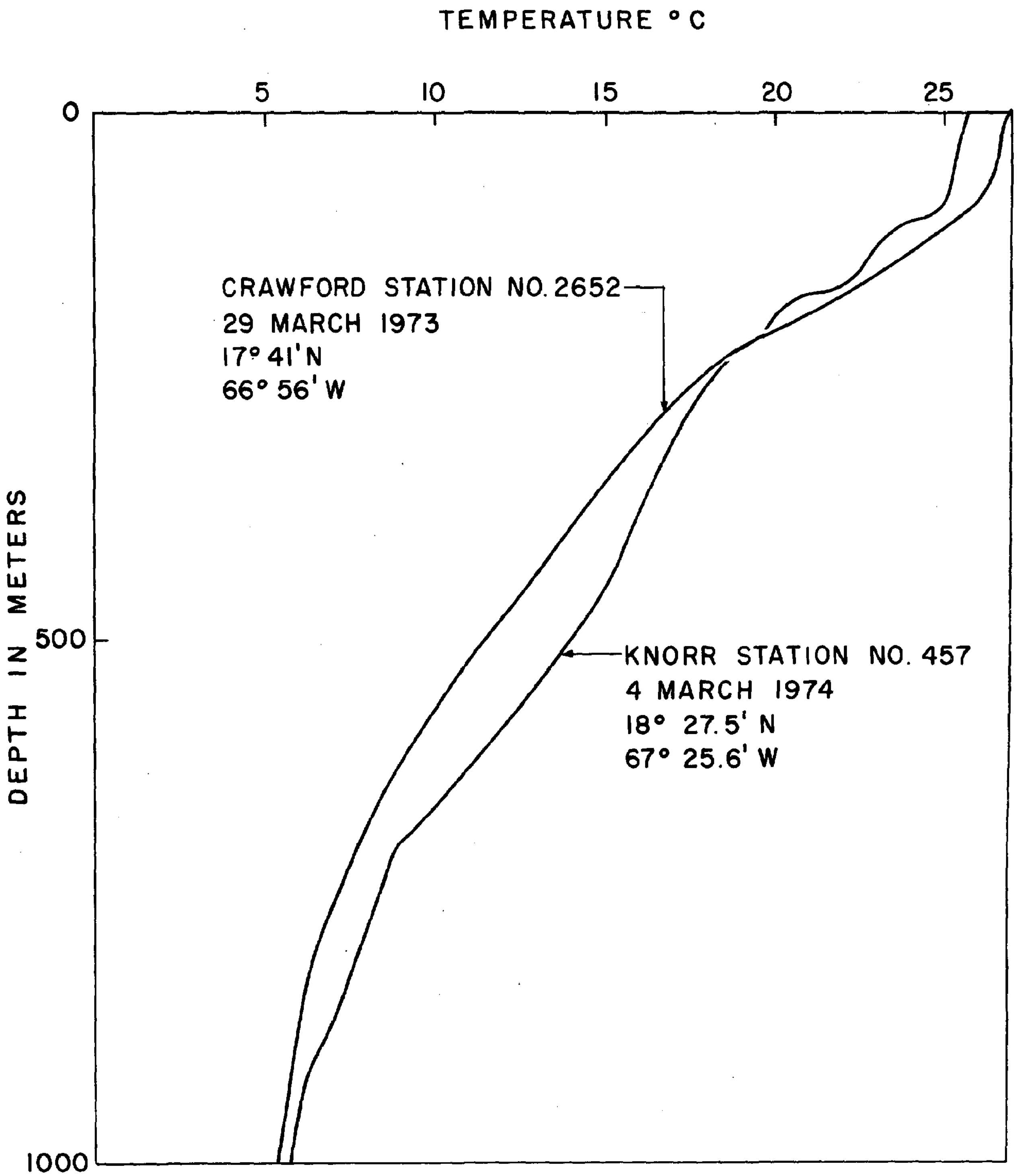


FIG. 74 TEMPERATURE PROFILES

PART IV: COMMENTS ON TRW SYSTEMS LIST OF DESIRABLE CRITERIA FOR AN OTEC TEST SITE

During the May 1975 OTEC workshop in Houston, Texas, TRW Systems presented a series of criteria they felt were essential for an OTEC test site. (Proceedings 3d OTEC Workshop, Houston, Texas, May 8-10 1975). We feel it pertinent to a consideration of the Puerto Rico site that these criteria be discussed in reference to the Puerto Rico site itself. Following are the TRW criteria with a discussion of each with reference to the Puerto Rico site.

1. Δ T profile for plant operation all year

   Almost any site deeper than 1000 meters around Puerto Rico will provide a Δ T of 20° C (36° F) between 1000 meters and the surface. Some sites can do better than this as we have shown for the south coast.

2. A site representative of an open ocean water mass:

   a) minimal run-off

   Puerto Rico has no great rivers, and the run-off from the existing rivers tends to remain close to shore until it mixes out. Any site around Puerto Rico fulfills this requirement if it reaches 1000 meters. On the south coast there is very little run-off.

   b) biologically, chemically and physically similar to open ocean

   As we have shown, there are really four water masses to be considered, not one, as the TRW list implies. Both the historical data (Part I) and the Point Tuna/Yabucoa data (Part II) show that any site around Puerto Rico that is more than 1000 meters deep will fulfill these requirements.

3. Availability of water management capabilities of the intake/output to test possible effects and uses such as mariculture.

   From our discussion of nutrients and density the possibility of mariculture seems to be somewhat questionable since it is advisable to let the outflux sink to avoid cooling the surface supply of hot water. However, if systems can be designed that would not interfere with plant operation, there is a vigorous program of aquaculture at the University of Puerto Rico; land based but capable of being redirected. There is a second vigorous mariculture program at the Lamont Laboratories at St. Croix, Virgin Islands.

4. Access in extreme conditions

   "Extreme conditions" around Puerto Rico means hurricanes, and there will be no access. The south coast is more sheltered than the north coast, however, see both "waves" in section I.8 and our comments on the Aguadilla site.

5. <u>Access roads to construction sites, airports, deep water port</u>

Puerto Rico has an adequate road system that handles heavy truck traffic both for the sugar cane industry and the containerized cargo of Puerto Rico Maritime Authority. This net extends throughout the island and passes close to any construction site imaginable. There are adequate airports in Roosevelt Roads Naval Base, San Juan, Ponce, and Aguadilla which handle heavy jet traffic (including Boeing 747s and Lockheed 1011s in San Juan) and smaller airports in Mayaguez and Arecibo and other island cities. There is a deep water port adjacent to the Point Tuna site at Yabucoa which commonly handles 600 foot tankers. There are also deep water ports at Roosevelt Roads Naval Base, San Juan, Mayaguez, Guayanilla and Ponce.

6. <u>Adequate power, housing and transport facilities</u>

The western end of Puerto Rico is supplied by the 115 KV island-wide grid. Housing, if for more than 100 men will probably have to be constructed, but it can be prefabricated or constructed very cheaply on the site due to the mild climate requirements and utilizing cheap concrete housing techniques which Puerto Rico pioneered. Transport facilities in Puerto Rico are adequate (see access roads above) and include the Puerto Rico Maritime Authority ships and an adequate supply of containerized vans and tractors, air freight companies that work with both jet and propeller driven aircraft, and excellent seagoing tugs.

Two active cement companies exist (Ponce Cement and San Juan Cement) and are presently supplying cement for updating Puerto Rico's highways into a modern four lane freeway system.

7. <u>University interest with an active and adequate computer facility</u>

The University of Puerto Rico has a department of Marine Sciences and Engineering Faculty with an active interest in the OTEC plant. The Mayaguez campus has a PDP 10 computer with about 150 K core, three disk drives and four magnetic tape drives...the installations replaced an IBM 360. The Engineering Faculty has a Digital PDP 11 and the Marine Sciences Department has a small 12 K PDP 8 computer at its La Parguera Marine Station.

PART V: CONCLUSIONS

1. A survey of historical oceanographic data for the area south of Puerto Rico shows that the temperature profile there is excellent for OTEC exploitation. The Δ T to 1000 meters is about 24° C (43° F) in September and October and always < 20°C (36°F). This has also been confirmed at a specific site off the southeast coast of Puerto Rico (just off Point Tuna and Yabucoa) during four separate hydrographic cruises during the period September 1975 to May 1976.

2. The continental slope at the Point Tuna/Yabucoa site is very steep and water depths of 1000 meters exist within 1½ miles of shore. Thus, the site is very suitable for a floating prototype plant tied to the Puerto Rico power grid by direct lines.

3. Due to geostrophic conditions in the Caribbean the warm mixed layer at the Point Tuna/Yabucoa site is generally quite thick and geostrophic calculation of currents at the site indicate that surface flows in the order of about 1/3 of a knot exist. Thus an OTEC plant is insured a plentiful supply of warm water for its boilers and proper engineering should easily avoid short circuiting the Δ T.

4. The supply of cold deep water at the site for the cooling cycle is virtually limitless.

5. The site is protected from north and northeast swell and a mild sea state exists all year round except for hurricanes. There is adequate access for constructing and servicing of a floating OTEC plant.

6. Adequate shore based facilities such as deep water ports, access roads, transportation facilities, housing, cement supply and air ports exist adjacent to, or near to, the site to allow for constructing and servicing of either a floating or shore based OTEC plant.

7. The salinity, temperature, nutrient distributions at the site are typical of an open tropical ocean even though the site has deep water within 1½ miles of shore making the site ideal for a prototype OTEC plant.

PART VI: SEMINARS PRESENTED BY UPR OTEC PROJECT STAFF

Ocean Thermal Energy Conversion - Presented to Department of Marine Sciences Seminar, August 1975.

Ocean Thermal Energy Conversion - Presented to NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, March 1976.

Ocean Thermal Energy Conversion - Presented to Puerto Rico Colegio of Engineers, April 1976.

Ocean Thermal Energy Conversion - Presented to International Friendship Club of Mayaguez, P.R., May 1976.

Energy From The Sea: Ocean Thermal Energy Conversion Possibilities In The Caribbean - Presented to CICAR-II Symposium, Caracas, Venezuela, 12-16 July 1976.

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